RESEARCH MEMORANDUM

SUMMARY REPORT ON ANALYTICAL EVALUATION OF AIR AND FUEL SPECIFIC-IMPULSE CHARACTERISTICS OF SEVERAL NONHYDROCARBON JET-ENGINE FUELS

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SUMMARY

An analytical evaluation of the air and fuel specific-impulse characteristics of magnesium, magnesium - octene-1 slurries, aluminum, aluminum - octene-1 slurries, boron, boron - octene-1 slurries, carbon, hydrogen, α-methylnaphthalene, diborane, and pentaborane, is presented herein.

Adiabatic constant-pressure combustion temperature, air specific impulse, fuel specific impulse, and equilibrium composition data are given for each fuel over a range of equivalence ratios. Data for octene-1, considered representative of aviation gasoline performance, are presented for comparison.

At an initial air temperature of 560° R and a pressure of 2 atmospheres, the adiabatic constant-pressure combustion temperature for magnesium at an equivalence ratio of 0.5 is 5507° R, and at an equivalence ratio of 1.0 the temperature is 6163° for aluminum, 5342° for boron, 4978° for pentaborane, 4848° for diborane, 4760° for slurries of 50 percent magnesium and 50 percent octene-1 by weight, 4680° for slurries of 50 percent boron and 50 percent octene-1 by weight, 4256° for hydrogen, 4188° for α-methylnaphthalene, 4180° for octene-1 and 4173° R for carbon.

Magnesium, magnesium - octene-1 slurries, aluminum, aluminum - octene-1 slurries, boron, boron - octene-1 slurries, pentaborane, diborane, and hydrogen, permit the attainment of air-specific-impulse values beyond the octene-1 limit. At any fixed air specific impulse below 135 seconds, the fuel-weight specific impulses of hydrogen, diborane, pentaborane, boron, and boron - octene-1 slurries are superior to octene-1.

The fuel-volume specific impulses of boron, aluminum, carbon, boron - octene-1 slurries, magnesium, pentaborane, α-methylnapthalene, and magnesium - octene-1 slurries, are superior to octene-1.

INTRODUCTION

High-speed flight has increased the demand for greater power per pound of engine, per unit volume of engine, per pound of fuel, and per unit volume of fuel. Emphasis has therefore been placed on the development of ram-jet engines, turbojet engines equipped with afterburners, and on special fuels that can be used in these engines.

The use of special fuels is warranted on the basis of the economics of high-speed flight; the cost of the fuel is often a small part of the total cost of aircraft operation, particularly in the case of the nonreturn guided missile. Fuels that provide higher thrust or fuels that reduce fuel weight or volume consumption or both are particularly desirable, because they offer increases in aircraft power and range.

The use of a wide variety of special fuels other than hydrocarbons is possible in the ram-jet engine and the afterburner, since there are practically no moving parts in the exhaust. Fuels that produce liquid or solid exhaust products can thus be used.

Preliminary comparisons of fuels that offer increased range and thrust can be based upon heating values per pound of fuel, per pound of combustion air, or per cubic foot of fuel. This calorific comparison of the fuels is adequate at very low fuel-air ratios where the dilution of the combustion products is great. However, in the ram jet and afterburner cycles, the exhaust temperatures are usually high; hence, the thermodynamic characteristics of the exhaust products introduce considerable discrepancies in the fuel performance based on heating values. It is advisable, therefore, to compare the performance of the fuels on the basis of a parameter that accounts for the thermodynamic characteristics of the exhaust and is a measure of the thrust-producing capability of various fuel types. Comparison of fuel performance in terms of thrust per pound of air and thrust per pound of fuel appears to be best based upon the parameters air specific impulse and fuel-weight specific impulse (ref. 1). These impulse functions, which conveniently express the total stream momentum per pound of air and per pound of fuel referenced at the exhaust-nozzle throat where the Mach number is equal to 1, are defined as:

Air specific impulse

$$S_a = \frac{1}{w_a} (pA + mV)^*$$

Fuel-weight specific impulse

$$S_f = \frac{1}{w_f} (pA + mV)^*$$

where * indicates the station at which the Mach number is equal to 1.0. (Symbols are defined in the following section.) The net internal thrust of an engine can be simply determined from the relation:

$$F_n = (pA + mV)_e - (pA + mV)_{in}$$

$$= w_a (\varphi) S_a - (pA + mV)_{in}$$

where φ is an area dependent function that relates total stream momentun at the end of the exit nozzle to air specific impulse (ref. 1).

The fuels that exhibit desirable impulse characteristics are generally the light metals and their hydrides. The status of combustion research of these fuels and others of interest is presented in reference 2, and pertinent physical and thermal properties of some of the representative fuels are presented in table I. Physical and combustion characteristics of several of the fuels listed in table I have been determined at the NACA Lewis laboratory; namely, diborane, aluminum, magnesium, and boron. Metal fuels have been burned in powder, wire, and slurry form (refs. 3 to 7). The slurry, a paint-like suspension of fine particles of metal in a hydrocarbon, has shown excellent combustion performance (refs. 4 to 7) and has indicated encouraging physical characteristics in laboratory-scale equipment (ref. 8). The physical characteristics of several high density hydrocarbons have been determined (ref. 9); the data for α-methylnaphthalene, a typical high density hydrocarbon of the condensed ring type, is included in table I.

The air and fuel specific impulse characteristics of the following potential jet-engine fuels have also been determined; namely, octene-1, aluminum, and aluminum - octene-1 slurries (ref. 10) magnesium, and magnesium - octene-1 slurries (ref. 11) diborane, pentaborane, boron, and boron - octene-1 slurries (ref. 12) and hydrogen, α-methylnaphthalene, and carbon (ref. 13). This report summarizes the aforementioned analytical reports and presents supplemental theoretical combustion performance for some of the slurry fuels.

SYMBOLS

The following symbols are used in this report:

A	area, sq ft
a/f	air-fuel ratio
F	stream thrust, lb
f/a	fuel-air ratio

g	acceleration due to gravity, ft/sec^2
$(H_T^o)_i$	molar chemical enthalpy of constituent i, cal/g-mole
I_r	ideal rocket specific impulse, lb-sec/lb mixture
M_i	molecular weight of constituent i
m	total mass flow, slugs/sec
n_i	number of moles of constituent i
p	static pressure, lb/sq ft
R	gas constant, ft-lb/(lb)(^oR)
S_a	air specific impulse, lb-sec/lb air
$S_{f,w}$	fuel-weight specific impulse, lb-sec/lb fuel
$S_{f,v}$	fuel-volume specific impulse, lb-sec/cu ft fuel
T	static temperature, ^oR
V	velocity, ft/sec
w	weight flow, lb/sec
X	weight fraction of solids in jet gases
ρ	density, lb/cu ft

Subscripts:

a	air
c	combustor outlet
e	exhaust-nozzle outlet
f	fuel
g	gaseous state
j	jet
in	inlet

l	liquid
n	net
s	solid

METHOD OF ANALYSIS

The method of analysis used was similar for all fuels. The general method is described in the following paragraphs and significant differences for the various fuels are indicated.

All fuels were assumed to be pure; air was assumed to be composed of 3.78 moles of nitrogen to every mole of oxygen. For convenience in calculation an inlet-air temperature of 560° R and an inlet pressure of 2 atmospheres were selected. The combustor inlet-air velocity was assumed to be negligible; friction effects were neglected.

At a given equivalence ratio (stoichiometric fuel fraction) the gas temperature and composition were calculated for an adiabatic constant-pressure combustion at 2 atmospheres by the matrix method of reference 14. All gases were assumed to follow the universal gas law. Thermodynamic data were obtained from reference 15 with certain exceptions. An empirical equation given in reference 16 for the heat capacity of magnesium oxide was used to obtain tabulated values of enthalpy, entropy, and heat capacity for magnesium oxide. The heat of formation of magnesium oxide is from reference 16, and the standard state entropy was taken from reference 17; suitable information for magnesium oxide with regard to vapor pressure at elevated temperatures, the boiling-point temperature, the latent heat of vaporization, and equilibrium constants, were not available. Consequently, magnesium oxide was considered a nondissociating condensed-phase constituent without significant vapor pressure.

The constituents considered in the equilibrium calculations, which were gaseous except as noted, are as follows:

Octene-1: CO_2, H_2O, H_2, O_2, N_2, CO, C, H, O, N, OH, NO

Magnesium: O_2, N_2, MgO_s, NO, O, N

Magnesium - octene-1 slurry: CO_2, H_2O, H_2, O_2, N_2, CO, MgO_s, NO, H, O, OH, C, N

Aluminum: O_2, N_2, $(Al_2O_3)_{s,l,g}$, Al, NO, AlO, O, N

Aluminum - octene-1 slurry: CO_2, H_2O, H_2, O_2, N_2, CO, C, $(Al_2O_3)_{s,l,g}$, Al, AlO, NO, H, O, N, OH

Boron: O_2, N_2, $(B_2O_3)_{s,l,g}$, B, BO, NO, N, O

Boron - octene-1 slurry: CO_2, H_2O, H_2, O_2, N_2, CO, $(B_2O_3)_{s,l,g}$, B, BO, BH, OH, NO, O, N, H, C

Hydrogen: H_2O, H_2, O_2, N_2, OH, H, O, N, NO

Carbon: CO_2, O_2, N_2, CO, C, O, N, NO

α-Methylnaphthalene: CO_2, H_2O, O_2, N_2, CO, C, H_2, NO, OH, H, O, N

Diborane: H_2O, O_2, N_2, $(B_2O_3)_{s,l,g}$, B, H_2, BH, NO, OH, H, O, BO, N

Pentaborane: H_2O, O_2, N_2, $(B_2O_3)_{s,l,g}$, B, H_2, BH, NO, OH, H, O, BO, N

The possible reactions of magnesium, aluminum, and boron with nitrogen to form nitrides were neglected because of inadequate thermodynamic data. The combustion products were assumed to expand isentropically at fixed composition to a pressure of 1 atmosphere at the end of a convergent nozzle.

When liquids or solids were present in the exhaust gases, it was assumed that: (1) the volume occupied by the condensed phase was negligible compared to the gas phase; (2) the condensed-phase particles were in thermal, velocity, and chemical equilibrium with the gas phase in the combustor; (3) the condensed-phase particles were in thermal and velocity equilibrium with the gas-phase particles in the exhaust nozzle.

From the gas composition and temperature, the jet velocity was calculated by using the following equation (ref. 18):

$$\frac{V_j}{g} = I_r = 9.328 \sqrt{\left(\frac{\Sigma n_i (H_T^o)_i}{\Sigma n_i M_i}\right)_c - \left(\frac{\Sigma n_i (H_T^o)_i}{\Sigma n_i M_i}\right)_e}$$

The air specific-impulse values were calculated from the following:

$$S_a = (1 + f/a)\left[\frac{V_j}{g} + \frac{RT}{V_j}(1-X)\right]$$

The Mach number at the exhaust nozzle resulting from expanding the combustion gases from 2 to 1 atmospheres, covered a range near unity. The error introduced into the air-specific-impulse function by assuming an exhaust-nozzle Mach number of 1 was 0.5 percent or less. Consequently, correction of the air specific-impulse function was omitted.

The fuel-weight specific impulse is defined as the stream thrust at the exhaust-nozzle exit per unit fuel weight flow and is a measure of fuel economy. Fuel-weight specific impulse was determined from the air specific impulse by the following relation:

$$S_{f,w} = S_a\,(a/f)$$

The fuel-volume specific impulse, which indicates the volume fuel consumption, was determined from the following relation:

$$S_{f,v} = S_{f,w}(\rho)$$

The density ρ of the slurries evaluated herein was assumed to follow the relation:

$$\frac{1}{\rho_{slurry}} = \frac{(\text{percent metal})}{100\ \rho_{metal}} + \frac{(\text{percent octene-1})}{100\ \rho_{octene\text{-}1}}$$

Magnesium slurries follow this relation up to about 80 percent metal by weight for magnesium, 80 percent for aluminum, and 60 percent for boron. These values do not necessarily represent the maximum slurry density but are maximum values that can be attained with powdered metals now available.

RESULTS AND DISCUSSION

Magnesium, Magnesium - Octene-1 Slurries, and Octene-1

Temperature. - The adiabatic constant-pressure combustion temperatures for magnesium, magnesium - octene-1 slurries, and octene-1, the hydrocarbon fuel, are presented in figure 1(a). The data are limited to a maximum combustion temperature of about 5500° R because of the lack of thermodynamic data as previously discussed. At an equivalence ratio of 0.5, an inlet-air temperature of 560° R, and an inlet-air pressure of 2 atmospheres, the adiabatic combustion temperature of pure magnesium is 5507° R. Increasing the magnesium concentration in a magnesium - octene-1 slurry increases the combustion temperature at all equivalence ratios investigated. It is significant that the maximum combustion temperature for the magnesium slurries occurs at progressivly higher equivalence ratios as the magnesium concentration is increased. This effect is a result of the high heating value of magnesium per pound of air since it was assumed that all magnesium combined with the oxygen present to form magnesium oxide. The tendency of high-concentration magnesium slurries to burn at equivalence ratios greater than 1.0 and to exhibit a higher heat release per pound of reactants than at an equivalence ratio of 1.0 has been experimentally established in reference 5. Reference 5 indicates that for a slurry consisting of finely powdered magnesium suspended in a hydrocarbon fuel, magnesium preferentially burned with the oxygen present and hence permitted the high heat release.

Air specific impulse. - Air-specific-impulse values for pure magnesium, several magnesium - octene-1 slurries, and octene-1 are presented in figure 1(b). Higher air-specific-impulse values can be achieved as

the percent magnesium in the slurry is increased. At an equivalence ratio of 0.5 the air specific impulse value for pure magnesium is 191 pound-seconds per pound of air, the same value (191 lb-sec/lb air) can be achieved with an 80 percent magnesium slurry (80 percent magnesium and 20 percent octene-1 by weight is implied) at an equivalence ratio of 0.8 or with a 60 percent magnesium slurry at an equivalence ratio of 1.04.

Fuel-weight specific impulse. - The variation of fuel-weight specific impulse with equivalence ratio for magnesium, magnesium - octene-1 slurries, and octene-1 is shown in figure 1(c). Increased metal concentration or increased equivalence ratio decreases the fuel-weight specific impulse, hence raising fuel consumption.

Relation between air- and fuel-weight specific impulse. - The variation of fuel-weight specific impulse with air specific impulse for magnesium, magnesium - octene-1 slurries, and octene-1 is shown in figure 1(d). These data were obtained by cross-plotting the data for the variation of fuel-weight specific impulse and air specific impulse with equivalence ratio from figures 1(b) and 1(c). The data in figure 1(d) are presented because comparisons of fuel economy for various fuels should be made at the same performance level; that is, at the same value of air specific impulse. Conversely, the relative air specific impulse of several fuels at a fixed fuel-economy value (fixed fuel-weight specific impulse) may be of interest. This information and the corresponding fuel-air ratios may be readily obtained from figure 1(d). Comparison of the fuels at any air specific-impulse value below 172.8 seconds, the maximum for octene-1, shows that a higher fuel specific impulse, that is, lower fuel consumption, is attainable with octene-1 than with the magnesium fuels. Air specific-impulse values higher than those attainable with the hydrocarbon, octene-1, can be achieved with magnesium slurries. At each air specific-impulse value higher than 172.8 seconds, there is an optimum metal concentration which will give the highest fuel-weight specific impulse (best fuel economy). Figure 1(e), a cross plot of figure 1(d), shows the approximate magnesium concentration that will give the highest fuel-weight specific impulse at any air specific-impulse value higher than the maximum for octene-1. Minor deviations in metal concentration from the values shown in figure 1(e) do not appreciably affect the fuel-weight specific impulse (fig. 1(d)).

Relation between air and fuel-volume specific impulse. - The fuels are compared on the basis of fuel-volume specific impulse in figure 1(f), which shows that the volume rate of fuel consumption at any fixed value of air specific impulse is reduced as metal concentration is increased. The curve for pure magnesium, although unrealistically based upon the solid density of magnesium, is included for comparison.

Aluminum and Aluminum - Octene-1 Slurries

Temperature. - The adiabatic constant-pressure combustion temperatures for aluminum, aluminum - octene-1 slurries, and octene-1 are presented in figure 2(a). At a combustor inlet-air temperature of 560° R, an inlet-air pressure of 2 atmospheres, and an equivalence ratio of 1.0, the combustion temperature for aluminum is 6163° R. The irregular nature of the aluminum temperature curve is due to a phase transition of aluminum sesquioxide from liquid to gas. Included in figure 2(a) are the theoretical flame temperatures for several concentrations of metal in aluminum - octene-1 slurries at an equivalence ratio of 1.0.

Air specific impulse. - The variation of air specific impulse with equivalence ratio for aluminum and octene-1 is presented in figure 2(b). At an equivalence ratio of 1.0, the air specific impulse for aluminum is 213.3 seconds; whereas, the maximum for octene-1 is 172.8 seconds. Included in this figure are the air-specific-impulse values for several aluminum slurries evaluated at an equivalence ratio of 1.0. The air specific impulse increases as the metal concentration in the slurry is increased.

Fuel-weight specific impulse. - The fuel-weight specific-impulse data are presented as a function of equivalence ratio for aluminum and octene-1 in figure 2(c). The fuel-weight specific impulse for aluminum slurries at several metal concentrations for an equivalence ratio of 1.0 is included in this plot. At a fixed equivalence ratio the fuel-weight specific impulse decreases with increases in aluminum concentration.

Relation between air- and fuel-weight specific impulse. - The variation of fuel-weight specific impulse with air specific impulse for aluminum and octene-1 is shown in figure 2(d). Included in this figure are data for several aluminum slurries evaluated at an equivalence ratio of 1.0. At the lower equivalence ratios and thus at the lower thrust levels, the fuel-weight specific impulse of the aluminum slurries is inferior to that of octene-1; however, aluminum and aluminum - octene-1 slurries do afford increases in thrust over and above that of the typical hydrocarbon fuel, octene-1.

Relation between air and fuel-volume specific impulse. - The fuels are compared on the basis of fuel-volume specific impulse in figure 2(e), where it is indicated that the volume rate of fuel consumption at fixed values of air specific impulse is reduced as metal content is increased. The pure aluminum curve is based upon the solid density of aluminum.

Boron and Boron - Octene-1 Slurries

Temperature. - The adiabatic constant-pressure combustion temperatures for boron and several boron - octene-1 slurries are shown in figure 3(a). The irregular nature of the boron temperature curve is due to a phase transition of boron sesquioxide from liquid to gas. Since the definition of the irregular curves necessitates the tedious calculation of many equilibrium-compositions, the data for the boron - octene-1 slurries were not completed in the range where this oxide transition occurs. The values for the boron - octene-1 slurries are presented at equivalence ratios of 0.1 to 0.3, and 1.0.

At an equivalence ratio of 1.0, an initial air temperature of 560° R, and an inlet-air pressure of 2 atmospheres, the combustion temperature increases as the percent boron is increased from the reference level for octene-1, 4180° R, to 5342° R, the value for 100 percent boron.

Air specific impulse. - The variation of air specific impulse with the equivalence ratio for boron, boron - octene-1 slurries, and octene-1 is presented in figure 3(b). At an equivalence ratio of 1.0, the air specific impulse value of 186.4 seconds is attainable with boron.

Fuel-weight specific impulse. - The variation of fuel-weight specific impulse with equivalence ratio for boron and boron - octene-1 slurries, and octene-1 is presented in figure 3(c).

Relation between air- and fuel-weight specific impulse. - The variation of fuel-weight specific impulse with air specific impulse for boron, boron - octene-1 slurries, and octene-1 is presented in figure 3(d). Higher fuel-weight specific-impulse values up to an air-specific-impulse value of 140, are attainable with boron or boron slurries compared to octene-1. However, because of the irregular nature of the boron performance curve resulting from the phase transition of boron sesquioxide from liquid to a gas, the fuel-weight specific impulse for octene-1 is superior in the air specific impulse range of 140 to 172 seconds.

The maximum value of air specific impulse for octene-1 is 172.8 seconds. The maximum values for air specific impulse were not calculated for boron and boron - octene-1 slurries. The calculations made for an equivalence ratio of 1.0 for the boron slurries indicate that the limiting air specific impulse for each of these fuels is significantly greater than that for the octene-1.

Relation between air- and fuel-volume specific impulse. - The comparison of boron, boron - octene-1 slurries, and octene-1 on the basis of fuel-volume specific impulse in figure 3(e) indicates that at fixed air specific-impulse values the fuel-volume specific impulse is improved

as the percent boron in the slurry is increased. The curve for pure boron although unrealistically based upon solid density is included for comparison.

Carbon, Hydrogen, and α-Methylnapthalene

Temperature. - The adiabatic constant-pressure combustion temperatures for carbon, hydrogen, α-methylnaphthalene, and octene-1 are shown in figure 4(a). The combustion temperatures for α-methylnaphthalene, which are essentially the same as the values for octene-1, coincide with the octene-1 curve.

At an equivalence ratio of 1.0, an inlet-air temperature of 560° R, and 2 atmospheres pressure, the combustion temperatures for carbon, hydrogen, and α-methylnaphthalene are 4173°, 4256°, and 4188° R, respectively, compared to 4180° R for octene-1.

Air specific impulse. - The variation of air specific impulse with equivalence ratio for carbon, hydrogen, α-methylnaphthalene, and octene-1 is presented in figure 4(b). At an equivalence ratio of 1.0, air-specific-impulse values are 166.1, 168.7, and 179.3 seconds for carbon, α-methylnaphthalene and hydrogen, respectively, compared with 170.4 seconds for octene-1.

Fuel-weight specific impulse. - The variation of fuel-weight specific impulse with equivalence ratio of carbon, α-methylnaphthalene, and hydrogen, is presented in figure 4(c).

Relation between air- and fuel-weight specific impulse. - Comparisons of carbon, α-methylnaphthalene, hydrogen, and octene-1 in terms of the fuel-weight specific impulse and air specific impulse are presented in figure 4(d). These data were obtained by cross-plotting the data for air and fuel-weight specific impulse presented in figures 4(b) and 4(c). In order of decreasing fuel-weight specific impulse at a given air specific impulse the fuels are as follows: hydrogen, octene-1, α-methylnaphthalene, and carbon.

The limiting value of air specific impulse for octene-1 is 172.8 seconds. The limiting values of air specific impulse were not calculated for hydrogen, α-methylnaphthalene and graphite carbon. Calculations for these latter fuels were limited to an equivalence ratio of 1.0.

Relation between air- and fuel-volume specific impulse. - A comparison of the air-specific-impulse and fuel-volume-specific-impulse characteristics of carbon, α-methylnaphthalene, hydrogen, and octene-1 is shown in figure 4(e). On a fuel-volume specific impulse basis at

a fixed air specific impulse, carbon and α-methylnaphthalene offer potential advantages over octene-1. Hydrogen is inferior to octene-1 on this basis. The densities used for liquid hydrogen, α-methylnaphthalene, graphite carbon, and octene-1 were: 4.426, 63.68, 141.1, and 44.4 pounds per cubic foot, respectively. The densities of octene-1, carbon, and α-methylnaphthalene were taken at room temperature. The density of hydrogen was taken at approximately its normal boiling point, -422.86° F. All densities are quoted for a pressure of 1 atmosphere.

Diborane and Pentaborane

Temperature. - The adiabatic constant-pressure combustion temperatures for diborane and pentaborane are compared with those of hydrogen and boron in figure 5(a).

At an equivalence ratio of 1.0 and an initial air temperature of 560° R, the combustion temperatures for diborane and pentaborane are 4848° and 4978° R, respectively.

Air specific impulse. - The variation of air specific impulse with equivalence ratio for diborane, pentaborane, hydrogen, and boron is presented in figure 5(b). The irregular nature of the curves for the fuels containing boron is due to the liquid to gas phase transition of boron sesquioxide, B_2O_3.

Fuel-weight specific impulse. - The variation of fuel-weight specific impulse with equivalence ratio for diborane and pentaborane compared with those of hydrogen and boron is presented in figure 5(c).

Relation between air- and fuel-weight specific impulse. - The variation of fuel-weight specific impulse with air specific impulse for pentaborane, diborane, boron, hydrogen, and octene-1 is presented in figure 5(d). These data were obtained by cross-plotting the data for air and fuel-weight specific impulse presented in figures 5(b) and 5(c). At fixed air-specific-impulse values, the fuels containing the greatest proportion of hydrogen exhibit the highest fuel-weight specific impulse. In the region where the liquid to gas phase transition of boron sesquioxide occurs, there is a more rapid decrease in fuel-weight specific impulse of the boron containing fuels than of octene-1 which has gaseous products over the air specific-impulse range of interest.

Relation between air and fuel-volume specific impulse. - A comparison of pentaborane, diborane, hydrogen, and boron in terms of fuel-volume specific impulse and air specific impulse is presented in figure 5(e). The densities assumed in calculating fuel-volume specific impulse corresponded to the liquid density of pentaborane, the

solid density of boron evaluated at room temperature, the liquid density for hydrogen at -423° F, and the liquid density for diborane at -134.5° F. The fuel-volume specific impulse for the boron and for the hydrogen are not very realistic, because the densities assumed may not be feasible in actual practice.

Equilibrium Composition Curves

The theoretical gaseous- and condensed-phase combustion-composition data in terms of the mole fraction of constituent as a function of equivalence ratio of octene-1, magnesium, 50 percent magnesium - octene-1 slurry, aluminum, boron, 50 percent boron - octene-1 slurry, carbon, hydrogen, α-methylnaphthalene, diborane, and pentaborane are presented in figures 6(a) to 6(k), respectively. These composition data were obtained simultaneously with the combustion-temperature data and were used to arrive at the air and fuel specific-impulse data. The data are particularly significant for the fuels that have constituents in the condensed phase at normal combustion temperatures, because these data indicate the regions of phase transition. Reference 3 indicates that, severe burner-wall deposits result when the combustion temperatures of aluminum fuels are in the region in which the fuel oxides are present as condensed liquid. In the case of the magnesium-slurry combustion, although solid exhaust products were present, the temperatures were below the melting point of the oxide and little or no deposits were present in the customary operating range (refs. 4 and 6).

The theoretical composition data for the 50 percent boron-octene-1 slurry are incomplete for the reasons listed in the boron, boron - octene-1 slurry section of the report.

Summary Comparisons

The adiabatic constant-pressure combustion temperature and impulse characteristics of magnesium, 50 percent magnesium - octene-1 slurry, aluminum, boron, 50 percent boron - octene-1 slurry, hydrogen, carbon, α-methylnaphthalene, diborane, pentaborane, and octene-1 are compared in figures 7(a), 7(b), and 7(c). In order to reduce the congestion of the figures only the two representative slurries containing 50 percent metal by weight are included in the summary comparisons.

Temperature. - The adiabatic constant-pressure combustion temperatures for the aforementioned fuels are presented in figure 7(a). The fuels listed in order of decreasing combustion temperature are: magnesium, aluminum, boron, pentaborane, diborane, 50 percent magnesium - octene-1 slurry, 50 percent boron - octene-1 slurry, hydrogen, α-methylnaphthalene, octene-1, and carbon.

Relation between air and fuel-weight specific impulse. - The aforementioned fuels are compared on the basis of fuel-weight specific impulse and air specific impulse in figure 7(b). The following fuels, evaluated below an air-specific-impulse value of 135 seconds, are listed in order of decreasing fuel-weight specific impulse: hydrogen, diborane, pentaborane, boron, 50 percent boron - octene-1 slurry, octene-1, α-methylnaphthalene, 50 percent magnesium - octene-1 slurry, carbon, aluminum, and magnesium. The limiting values of air specific impulse were not calculated for a majority of fuels; only in the case of octene-1 was the limit determined. However, all fuels except carbon and α-methylnaphthalene appear to have a maximum air specific impulse higher than that for octene-1. Magnesium has the highest air specific impulse (thrust) of the fuels evaluated.

Relation between air- and fuel-volume specific impulse. - Representative fuels were evaluated in terms of fuel-volume specific impulse at various air specific-impulse values (fig. 7(c)). The fuels evaluated in order of decreasing fuel-volume specific impulse at an air specific-impulse below 120 seconds are as follows: boron, aluminum, carbon, 50 percent boron - octene-1 slurry, magnesium, pentaborane, α-methylnaphthalene, 50 percent magnesium - octene-1 slurry, octene-1, diborane, and hydrogen.

SUMMARY OF RESULTS

An analytical evaluation of the air and fuel specific-impulse characteristics of magnesium, magnesium - octene-1 slurries, aluminum, aluminum - octene-1 slurries, boron, boron - octene-1 slurries, carbon, hydrogen, α-methylnaphthalene, diborane, and pentaborane, is presented herein. At an inlet-air temperature of 560° R, a pressure of 2 atmospheres, and for the other conditions assumed in this analysis the following results were obtained:

1. The adiabatic constant-pressure combustion temperature for magnesium at an equivalence ratio of 0.5 was 5507° R, and at an equivalence ratio of 1.0 the temperature is 6163° for aluminum, 5342° for boron, 4978° for pentaborane, 4848° for diborane, 4760° for slurries of 50 percent magnesium and 50 percent octene-1 by weight, 4680° for slurries of 50 percent boron and 50 percent octene-1 by weight, 4256° for hydrogen, 4188° for α-methylnaphthalene, 4180° for octene-1, and 4173° R for carbon. Only carbon exhibited a lower combustion temperature than the combustion temperature of octene-1.

2. The air-specific-impulse value for magnesium at an equivalence ratio of 0.5 was 191 pound-seconds per pound of air; the following

values were obtained at an equivalence ratio of 1.0: aluminum, 213.3; boron, 186.4; pentaborane, 186.0; diborane, 185.2; 50 percent magnesium and 50 percent octene-1 slurry, by weight, 184; hydrogen, 179.3; 50 percent boron and 50 percent octene-1 slurry, by weight, 178; octene-1, 170.4; α-methylnaphthalene, 168.7; and carbon, 166.1.

3. At a fixed air specific impulse below 135 seconds, the fuel weight specific impulses of hydrogen, diborane, pentaborane, boron, and boron-octene-1 slurries, by weight, were superior to octene-1. At air specific-impulse values of about 135 and higher, the phase transition of boron sesquioxide from the liquid to the gas phase, in the fuels containing boron, reduces the fuel specific impulse relative to octene-1.

4. The fuel-volume specific impulses of boron, aluminum, carbon, slurries of 50 percent boron and 50 percent octene-1 by weight, magnesium, pentaborane, α-methylnaphthalene, and slurries of 50 percent magnesium and 50 percent octene-1 by weight, were superior to octene-1..

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

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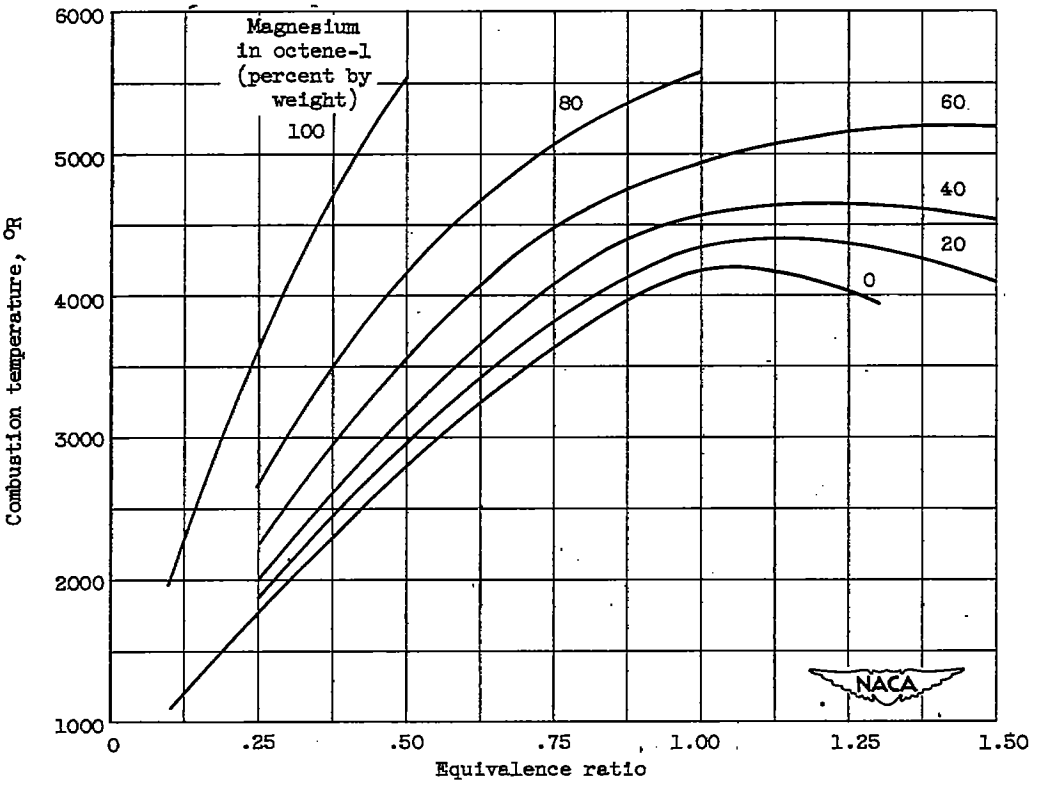
TABLE I.- HEATING VALUES OF HIGH ENERGY FUELS

[Except as noted, heats of combustion calculated from heats of formation at 25° C from ref. 19, melting and boiling points from ref. 20.]

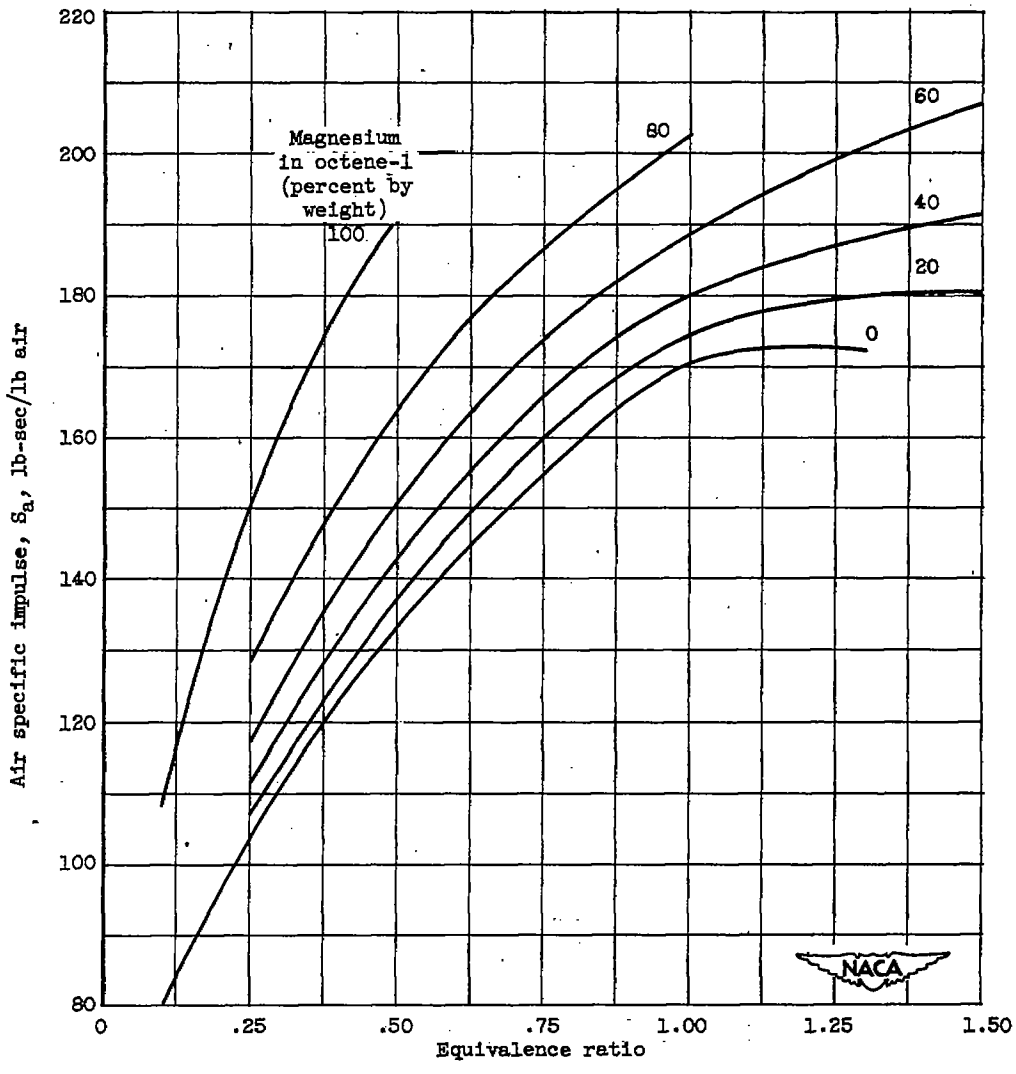
Fuel	Melting point, °F	Boiling point, °F	Specific gravity	Stoichiometric fuel-air ratio	Oxides (a)	Heat of combustion		
						Btu/lb	Btu/cu ft	Btu/lb air
Acetylene	-115.2	-118.5 (sublimes)	0.6208 (-119° F)	0.0755	CO_2, H_2O	20,734	803,556	1565
Aluminum	1219.5	4442	2.702	.2608	Al_2O_3	13,309	2,244,979	3471
Beryllium	2462	2786 (5 mm Hg)	1.85	.1307	BeO	29,140	3,365,447	3809
Boron	4172	4622	2.3	.1046	B_2O_3	25,100	3,603,986	2625
Carbon (graphite)	6606-87 (sublimes)	7600	2.25	.0871	CO_2	14,087	1,978,712	1227
Diborane	-265.9	-134.5	0.447 (-170° F)	.0669	B_2O_3, H_2O	31,370	875,394	2099
Hydrogen	-434.52	-423.0	0.070 (liquid)	.0292	H_2O	51,571	225,364	1506
Lithium	367	2437	0.534	.2013	Li_2O	18,460	615,396	3716
Lithium hydride	1256		0.82	.1152	Li_2O, H_2O	17,760	909,156	2046
Magnesium	1204	2012-48	1.74 (41° F)	.3527	MgO	10,639	1,155,664	3752
Pentaborane	-51.9	32 (66 mm Hg)	0.61 (32° F)	.0763	B_2O_3, H_2O	29,127	1,109,193	2222
Silicon	2588	4700	2.4	.2035	SiO_2	13,170	1,973,234	2680
Silane	-301	-169.2	0.68 (-301° F)	.1164	SiO_2, H_2O	17,160	728,463	1997
Titanium	3300	>5400	4.5 (68° F)	.3473	TiO_2	8,187	2,299,952	2843
α-Methyl-naphthalene[b]	-22.90	471.96	1.020	.0764	CO_2, H_2O	17,015	1,083,462	1300

[a]Condensed phases at approximately room temperature except H_2O_g.
[b]Data from ref. 9.



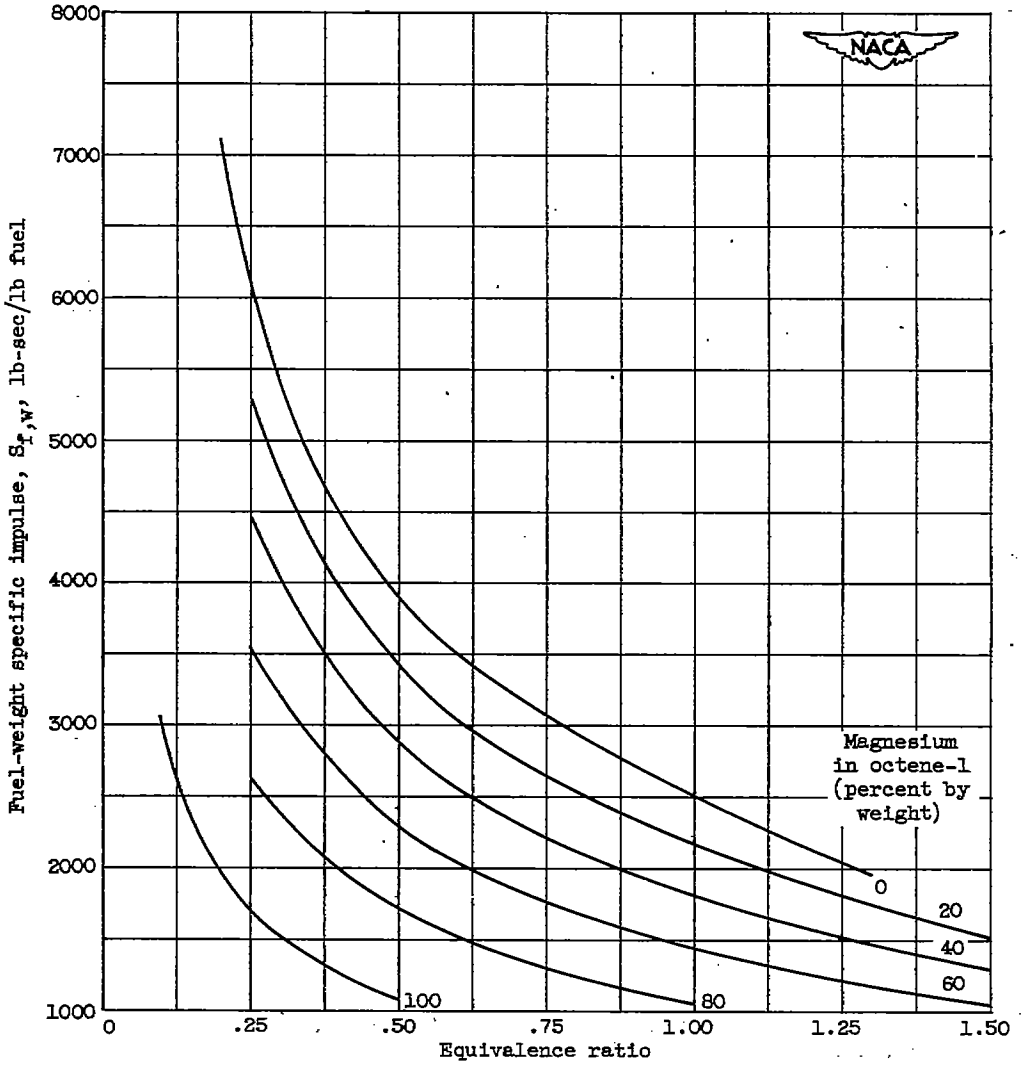
(a) Variation of adiabatic constant-pressure combustion temperature with equivalence ratio.

Figure 1. - Theoretical combustion performance for magnesium, magnesium - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



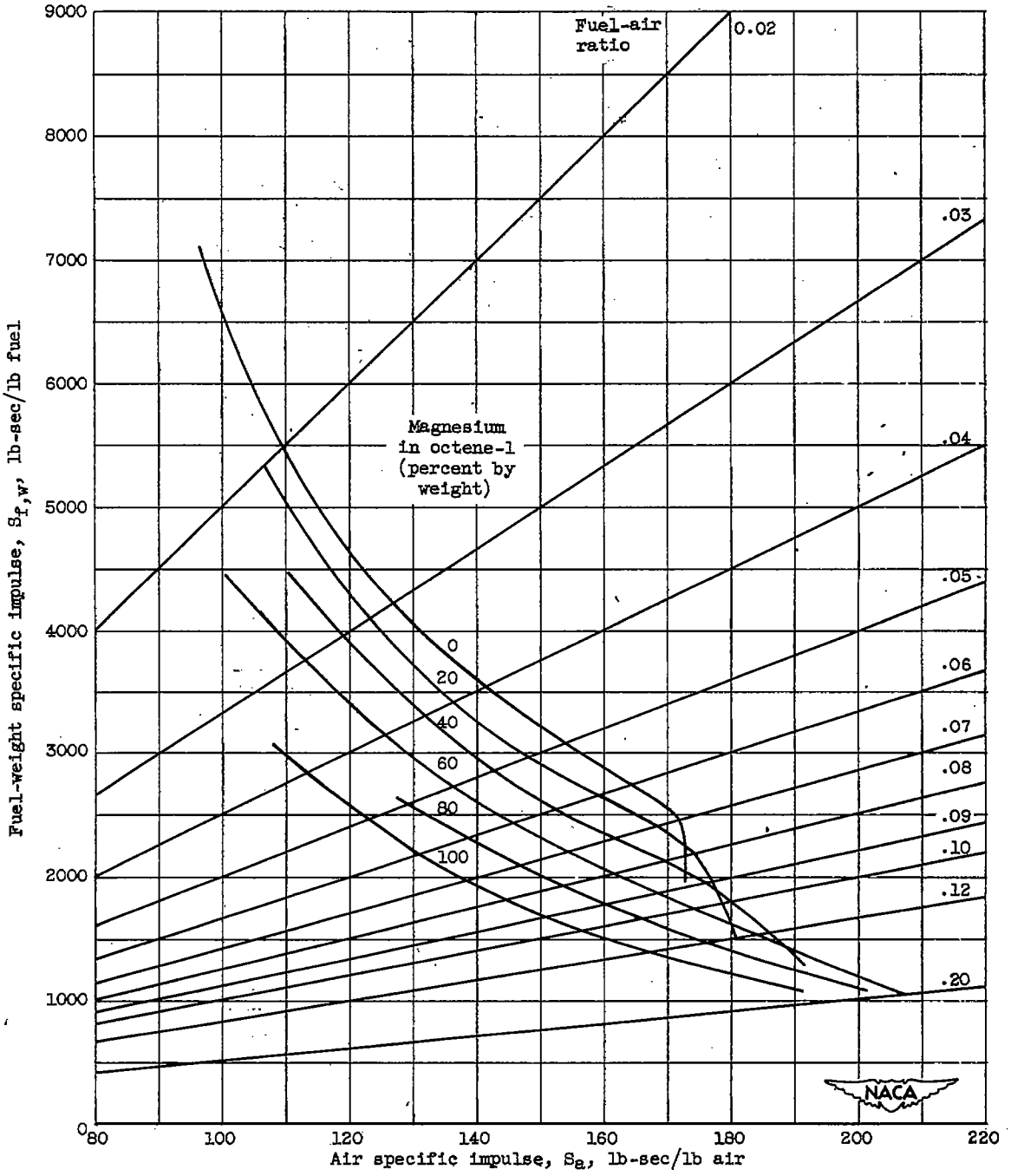
(b) Variation of air specific impulse with equivalence ratio.

Figure 1. - Continued. Theoretical combustion performance for magnesium, magnesium - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



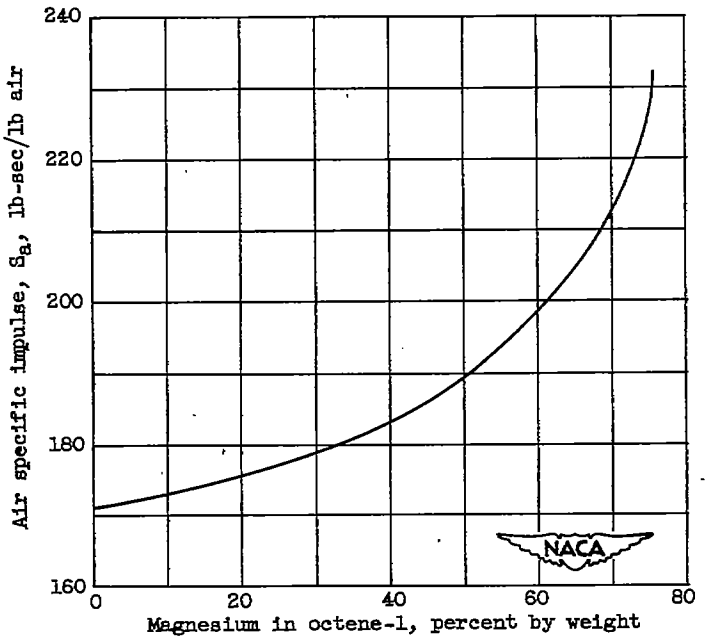
(c) Variation of fuel-weight specific impulse with equivalence ratio.

Figure 1. - Continued. Theoretical combustion performance for magnesium, magnesium - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



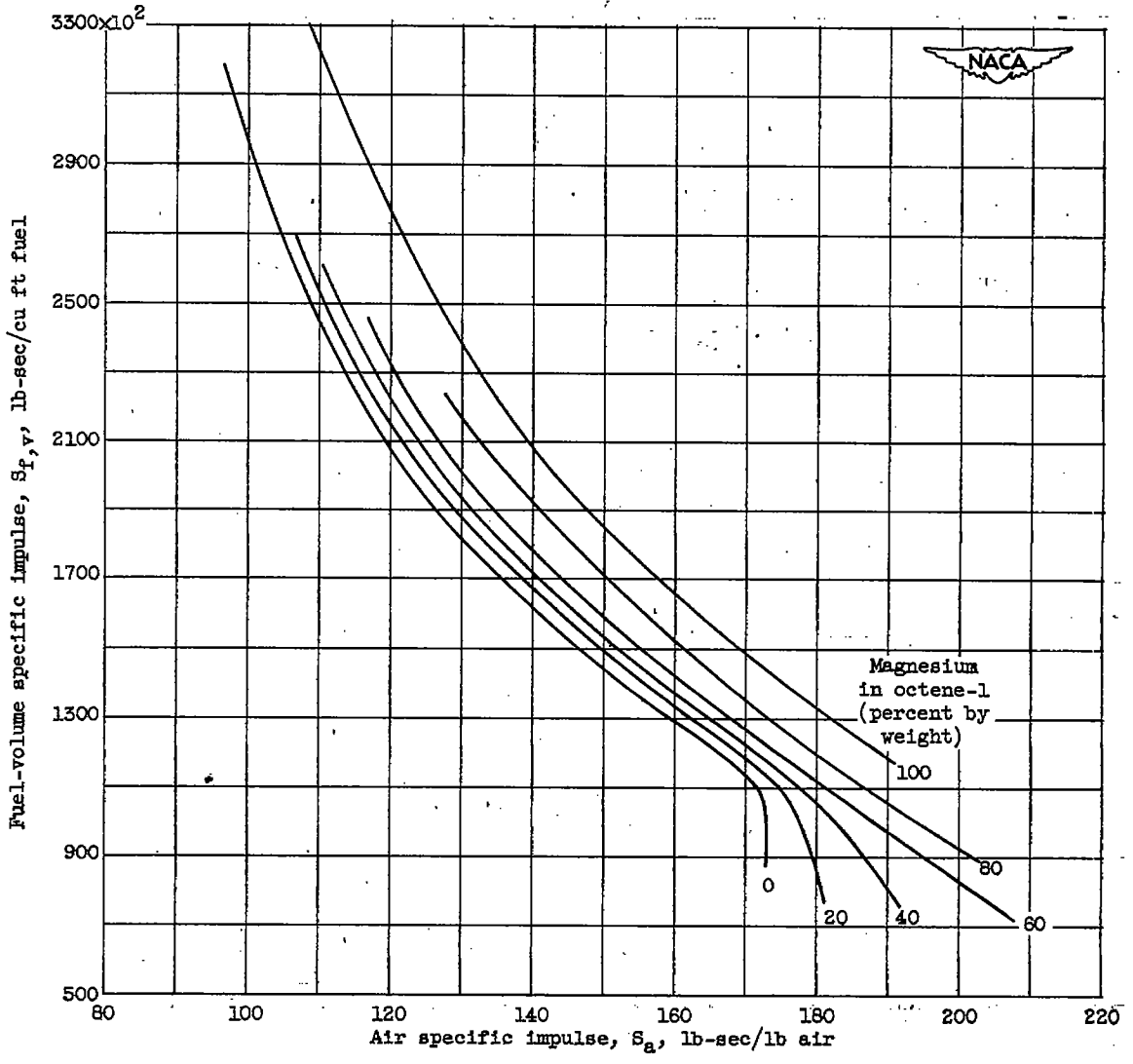
(d) Variation of fuel-weight specific impulse with air specific impulse.

Figure 1. - Continued. Theoretical combustion performance for magnesium, magnesium - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



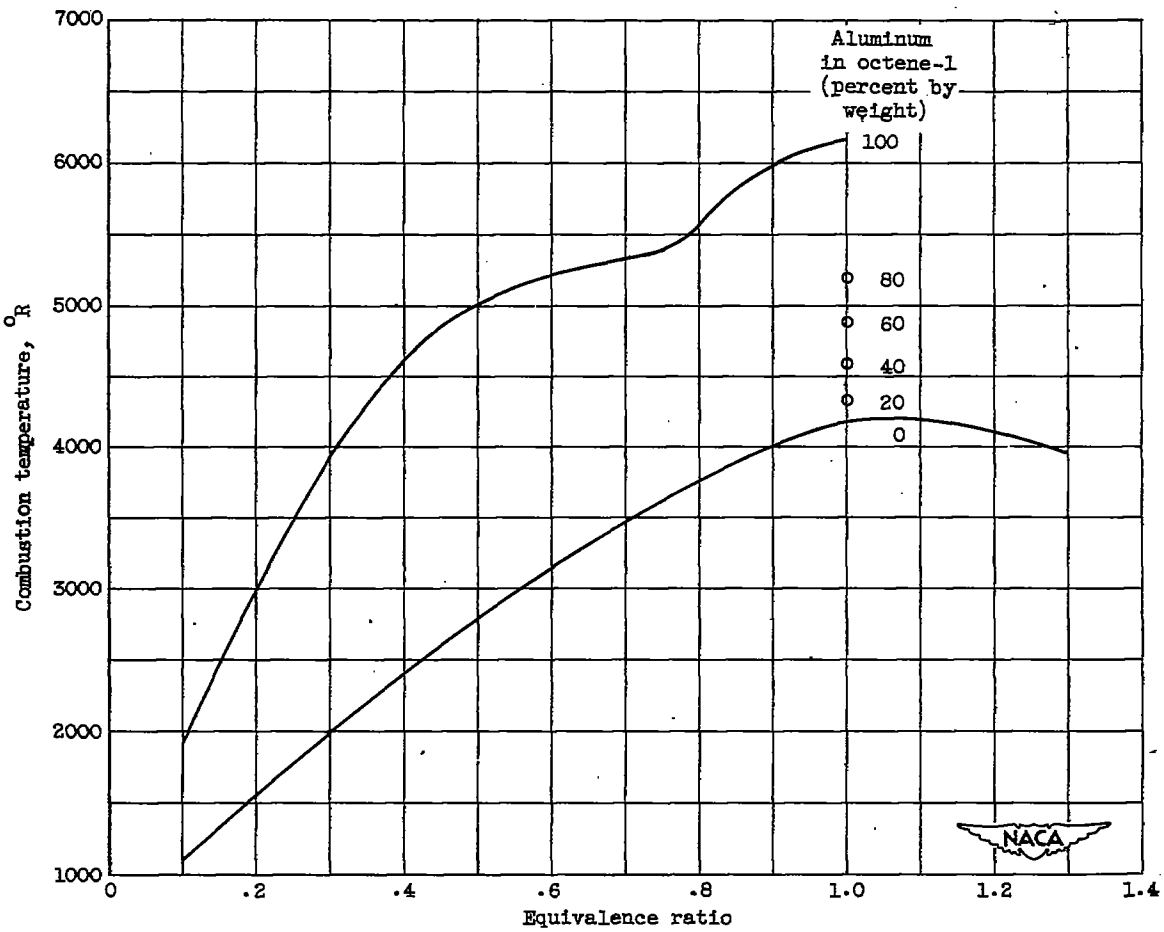
(e) Optimum metal concentration in magnesium - octene-1 slurries for maximum fuel-weight specific impulse.

Figure 1. - Continued. Theoretical combustion performance for magnesium, magnesium - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



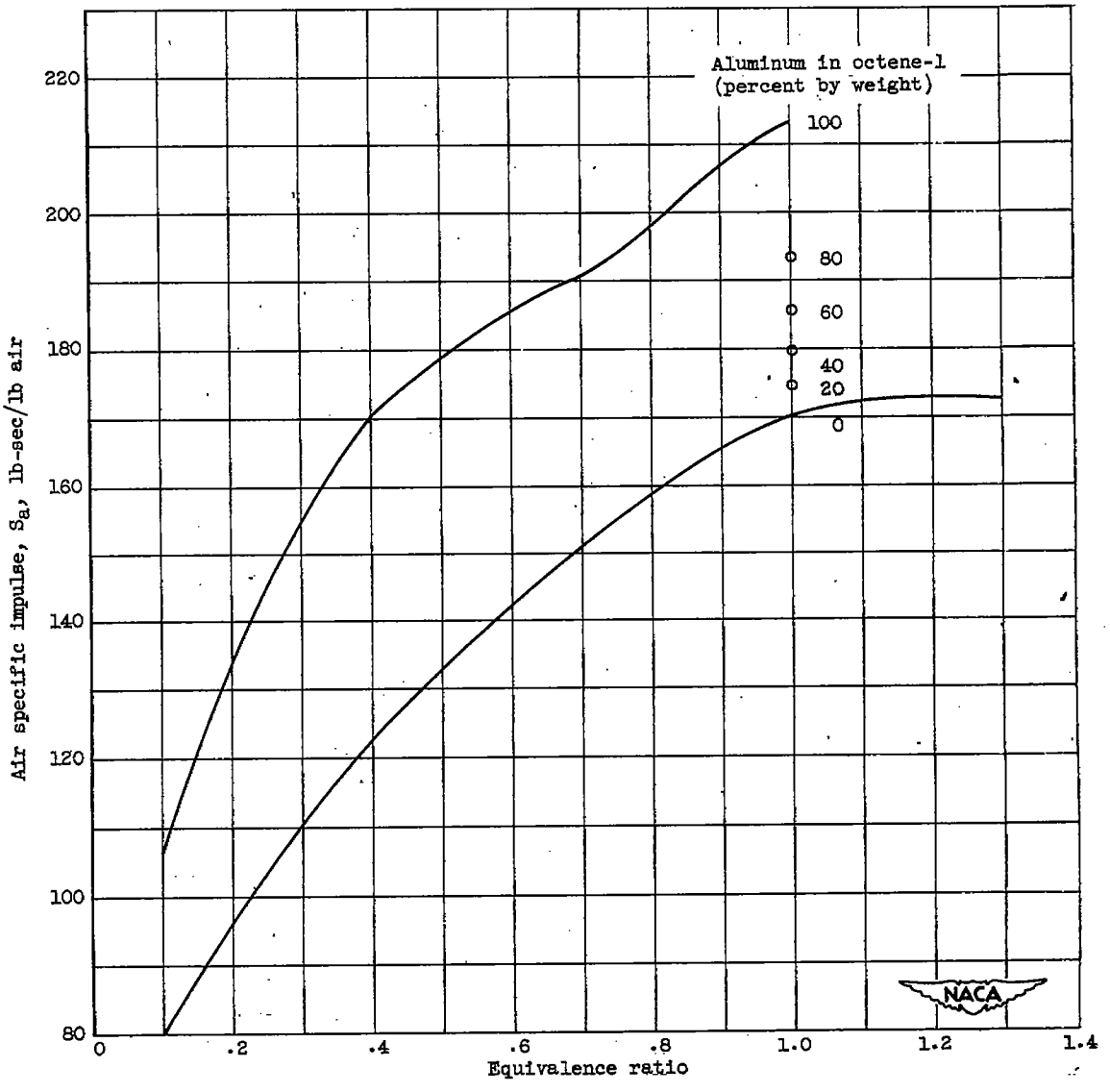
(f) Variation of fuel-volume specific impulse with air specific impulse.

Figure 1. - Concluded. Theoretical combustion performance for magnesium, magnesium - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



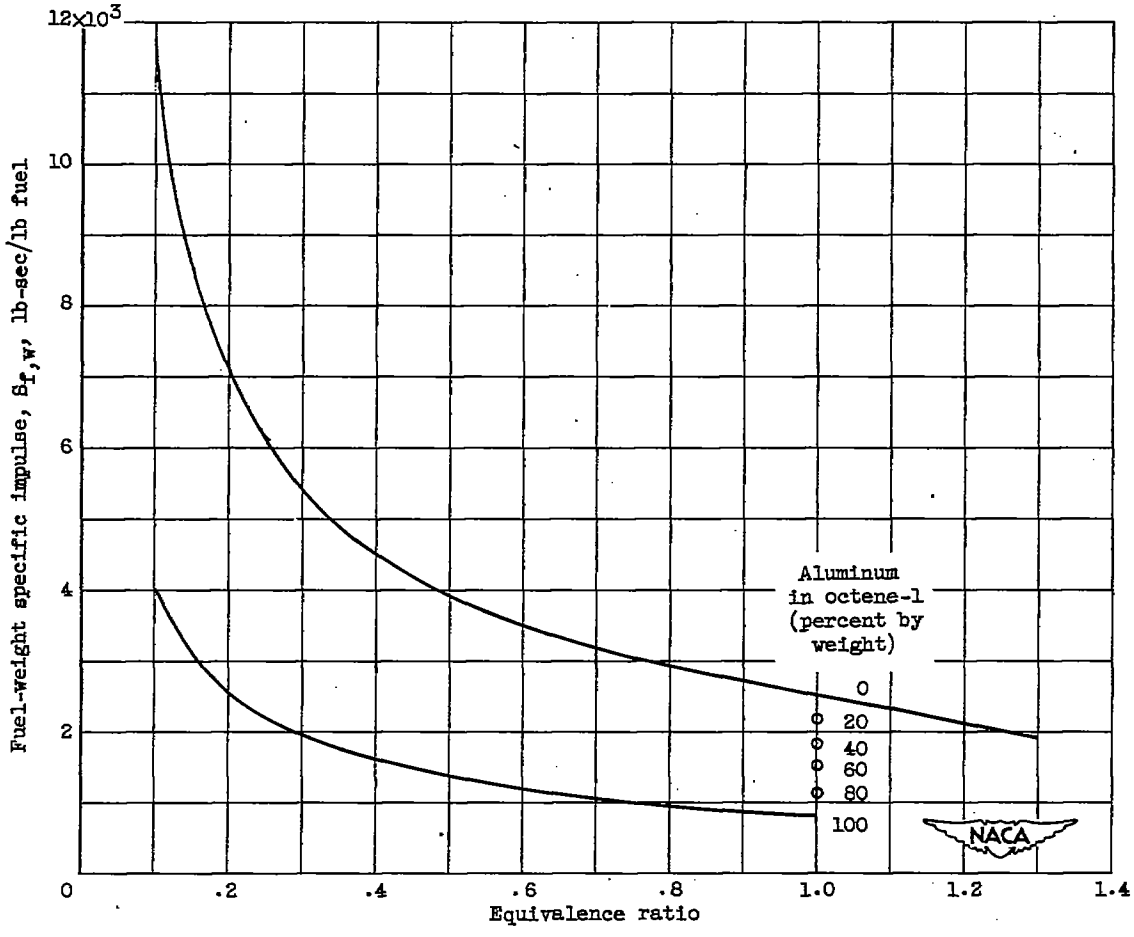
(a) Variation of adiabatic constant-pressure combustion temperature with equivalence ratio.

Figure 2 - Theoretical combustion performance for aluminum, aluminum - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



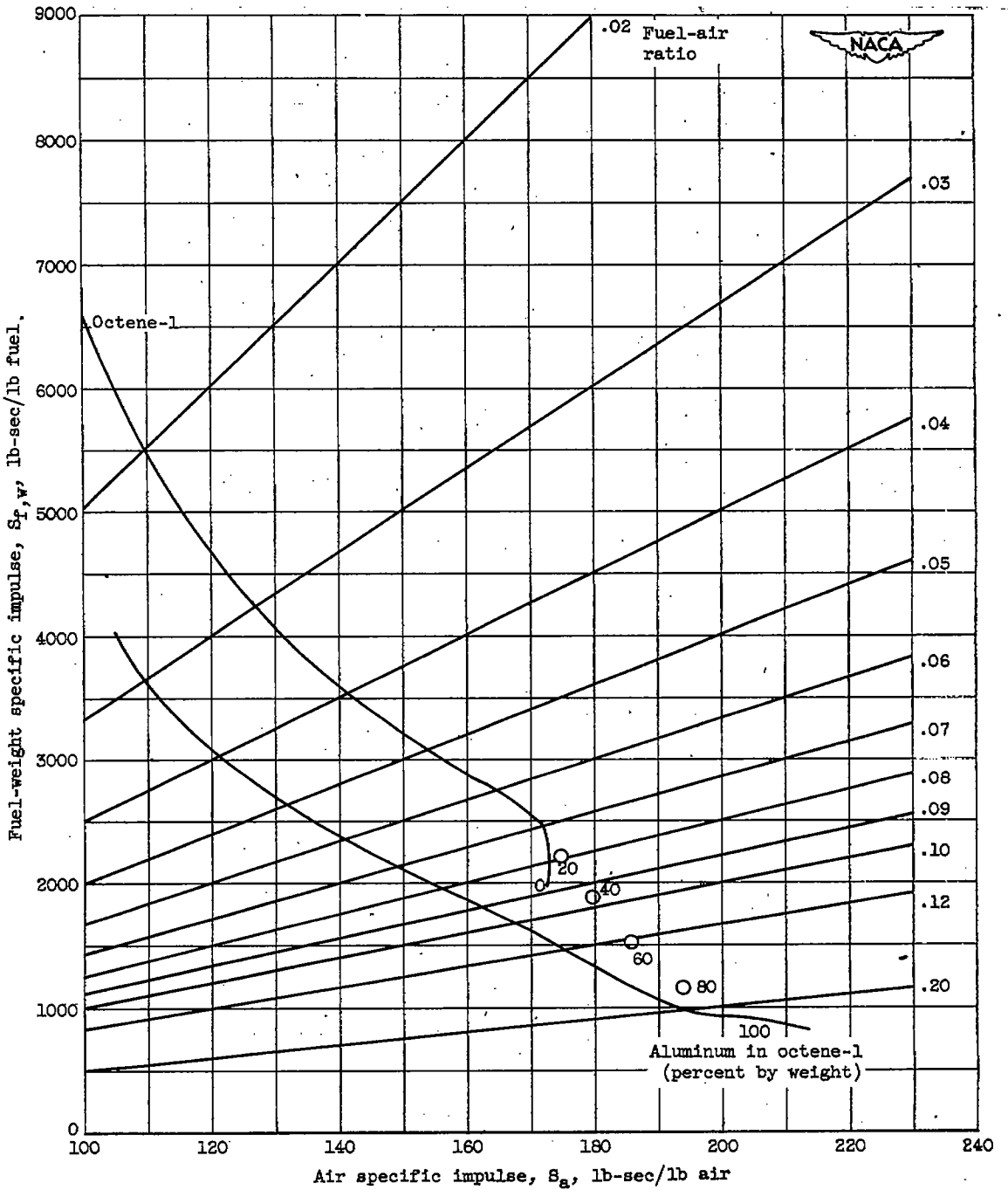
(b) Variation of air specific impulse with equivalence ratio.

Figure 2. - Continued. Theoretical combustion performance for aluminum, aluminum - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



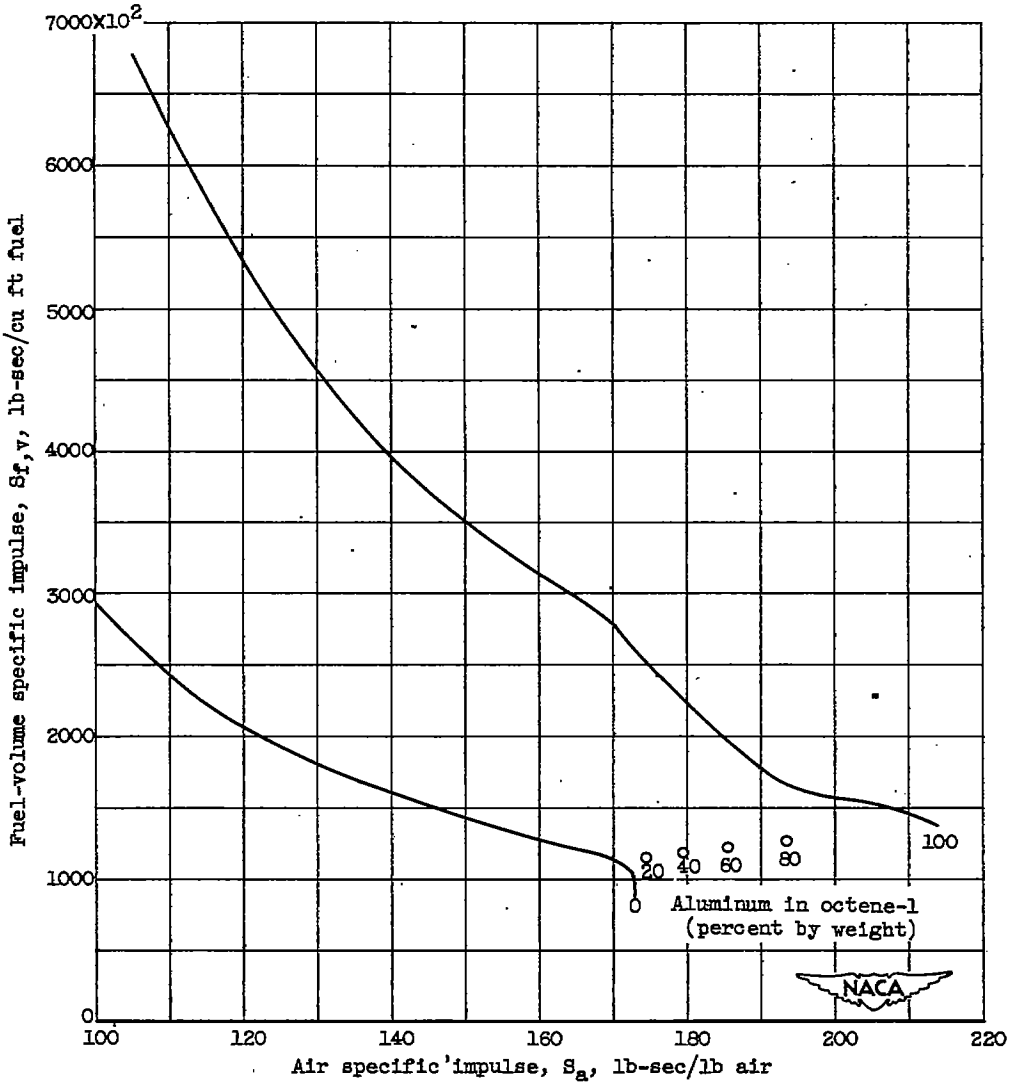
(c) Variation of fuel-weight specific impulse with equivalence ratio.

Figure 2. - Continued. Theoretical combustion performance for aluminum, aluminum - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



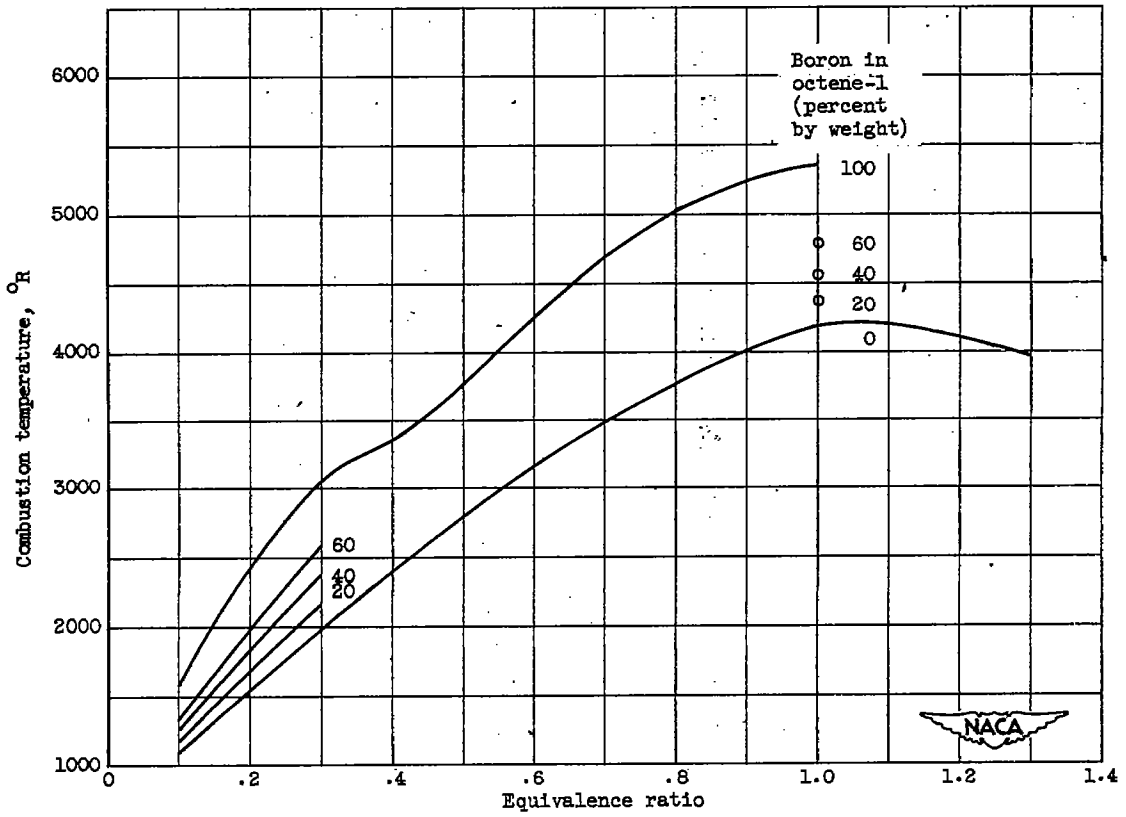
(d) Variation of fuel-weight specific impulse with air specific impulse.

Figure 2. - Continued. Theoretical combustion performance for aluminum, aluminum - octene-1 slurries and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



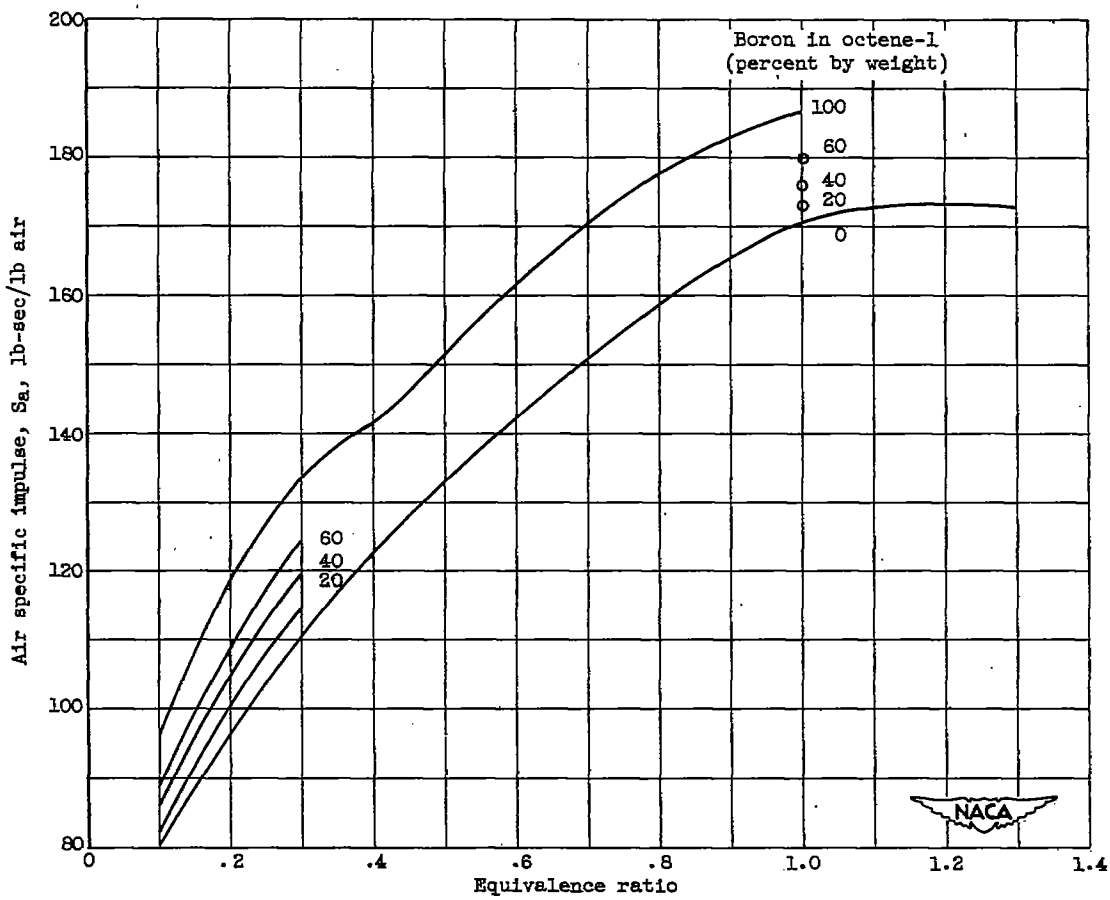
(e) Variation of fuel-volume specific impulse with air specific impulse.

Figure 2. - Concluded. Theoretical combustion performance for aluminum, aluminum - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



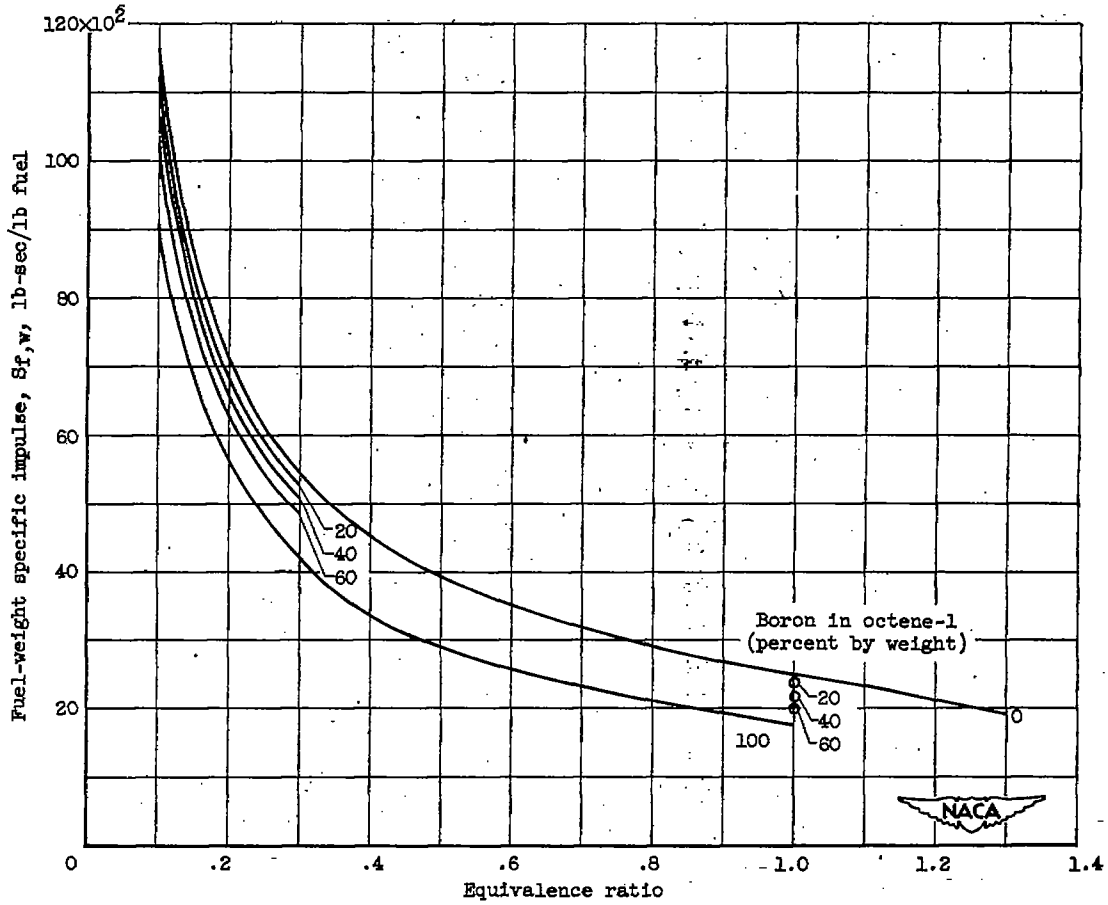
(a) Variation of adiabatic constant-pressure combustion temperature with equivalence ratio.

Figure 3. - Theoretical combustion performance for boron, boron - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



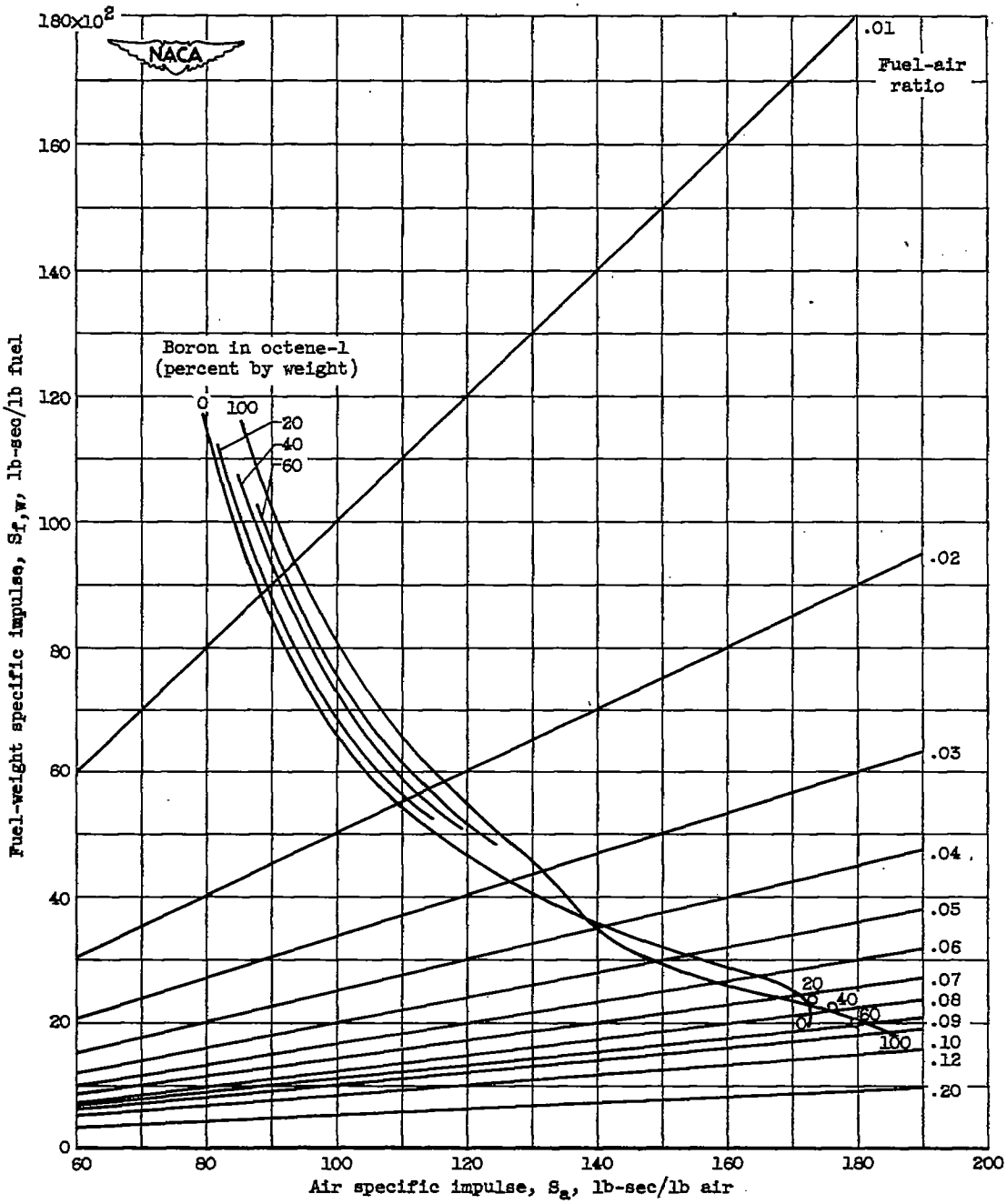
(b) Variation of air specific impulse with equivalence ratio.

Figure 3. - Continued. Theoretical combustion performance for boron, boron - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



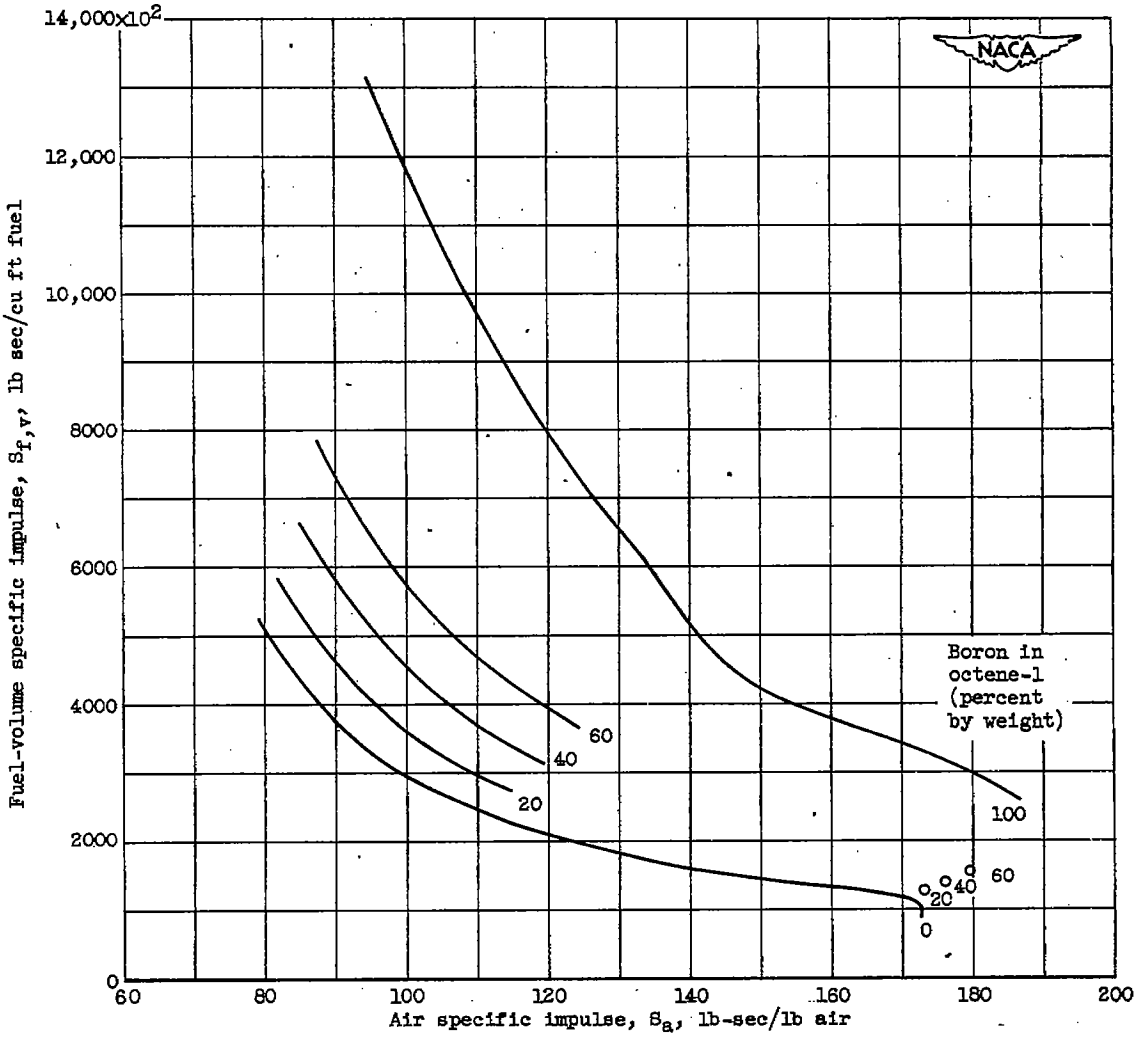
(c) Variation of fuel-weight specific impulse with equivalence ratio.

Figure 3. - Continued. Theoretical combustion performance for boron, boron - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



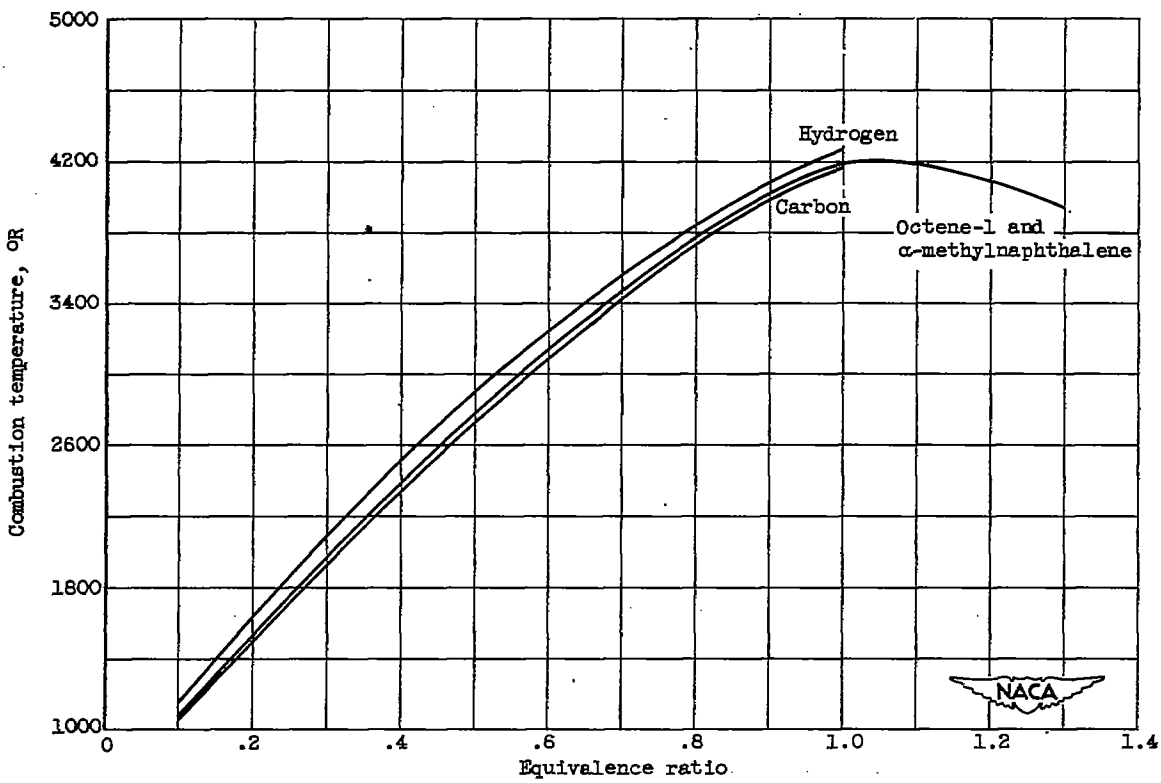
(d) Variation of fuel-weight specific impulse with air specific impulse.

Figure 3. - Continued. Theoretical combustion performance for boron, boron - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



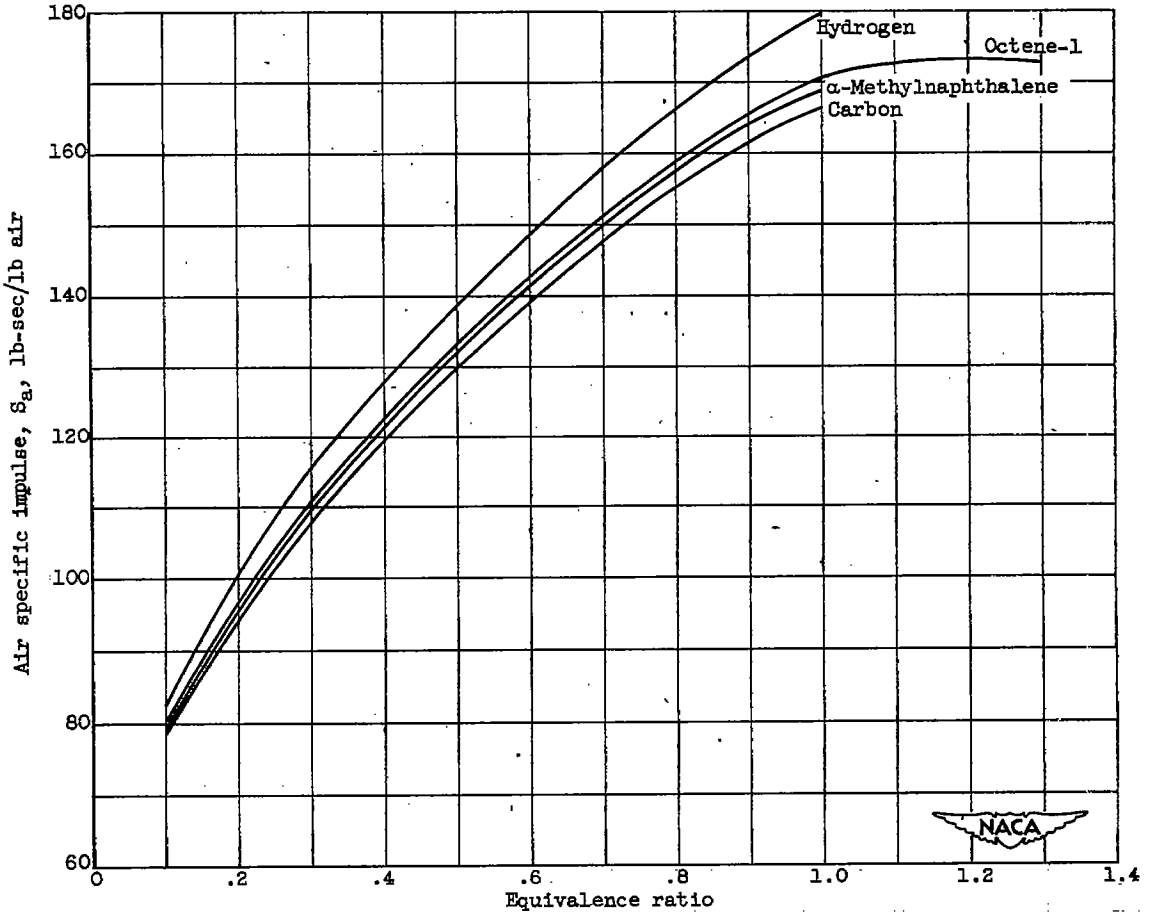
(e) Variation of fuel-volume specific impulse with air specific impulse.

Figure 3. - Concluded. Theoretical combustion performance for boron, boron - octene-1 slurries, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



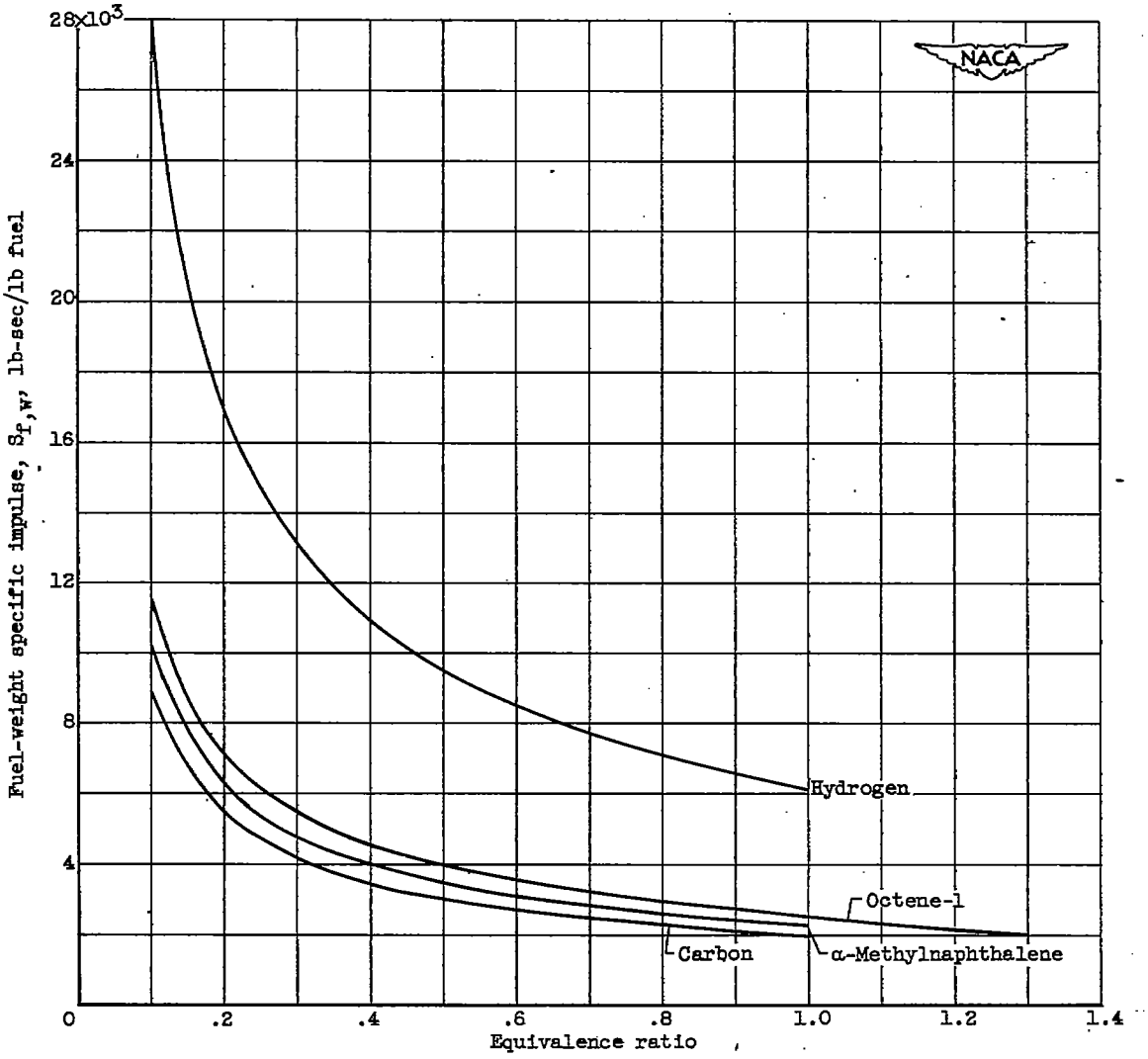
(a) Variation of adiabatic constant-pressure combustion temperature with equivalence ratio.

Figure 4. - Theoretical combustion performance for hydrogen, carbon, α-methylnaphthalene, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



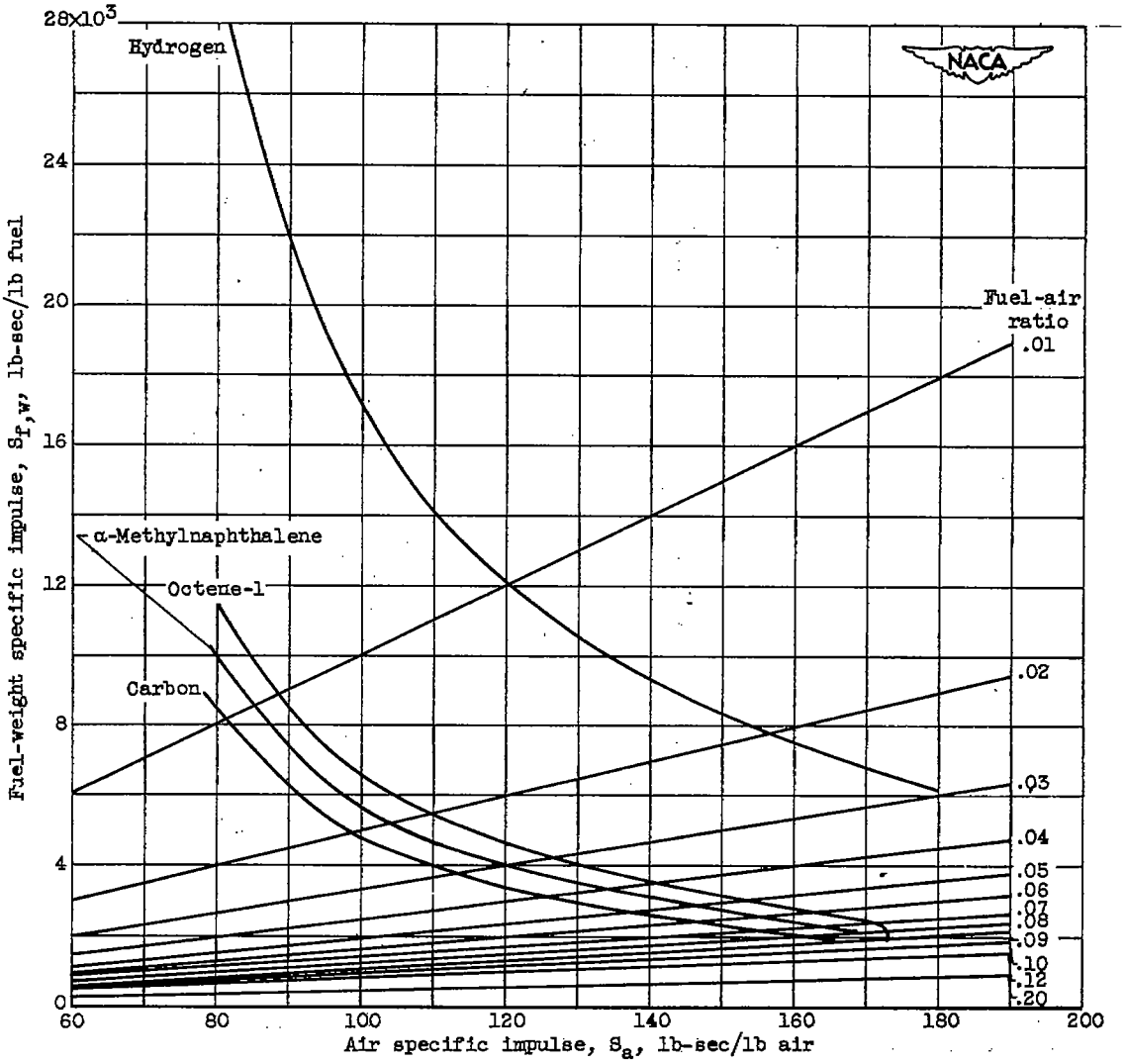
(b) Variation of air specific impulse with equivalence ratio.

Figure 4. - Continued. Theoretical combustion performance for hydrogen, carbon, α-methylnaphthalene, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



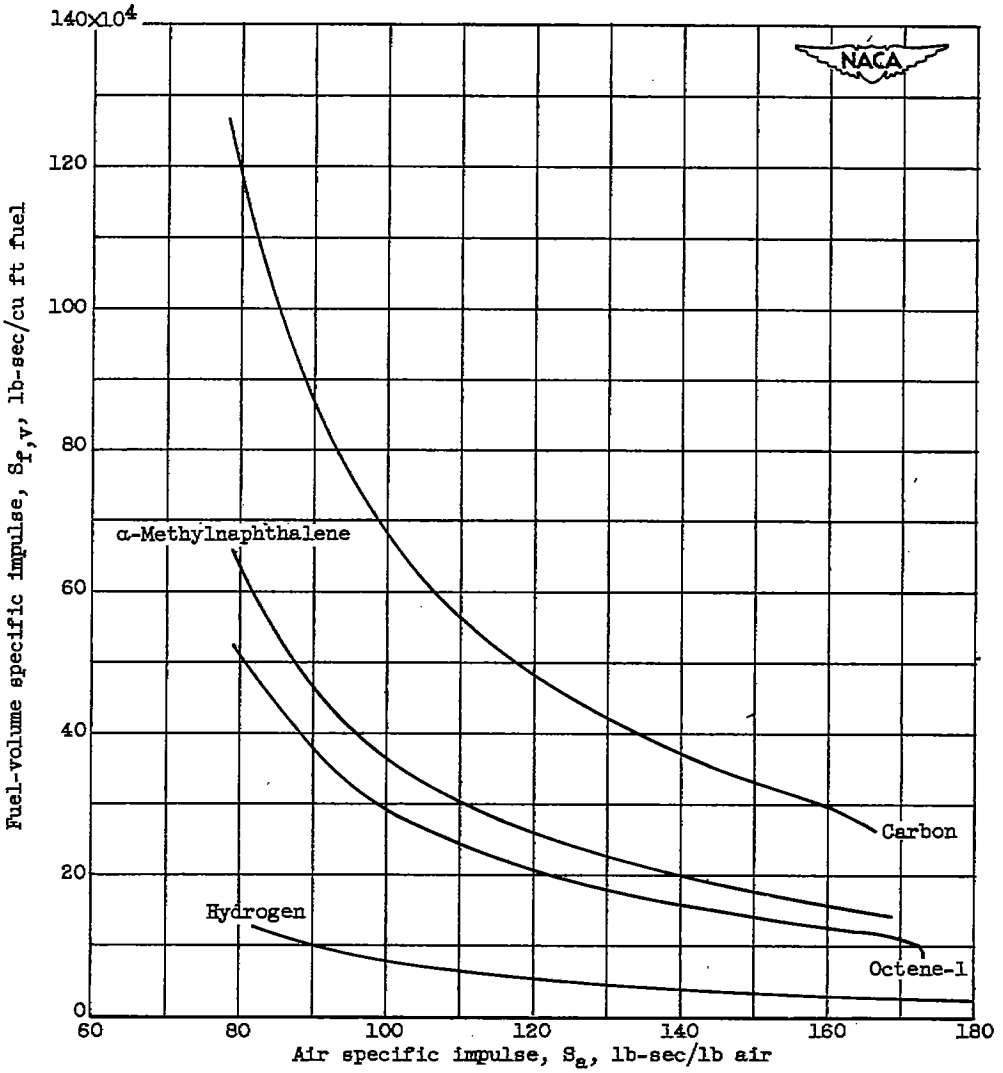
(c) Variation of fuel-weight specific impulse with equivalence ratio.

Figure 4. - Continued. Theoretical combustion performance for hydrogen, carbon, α-methylnaphthalene, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



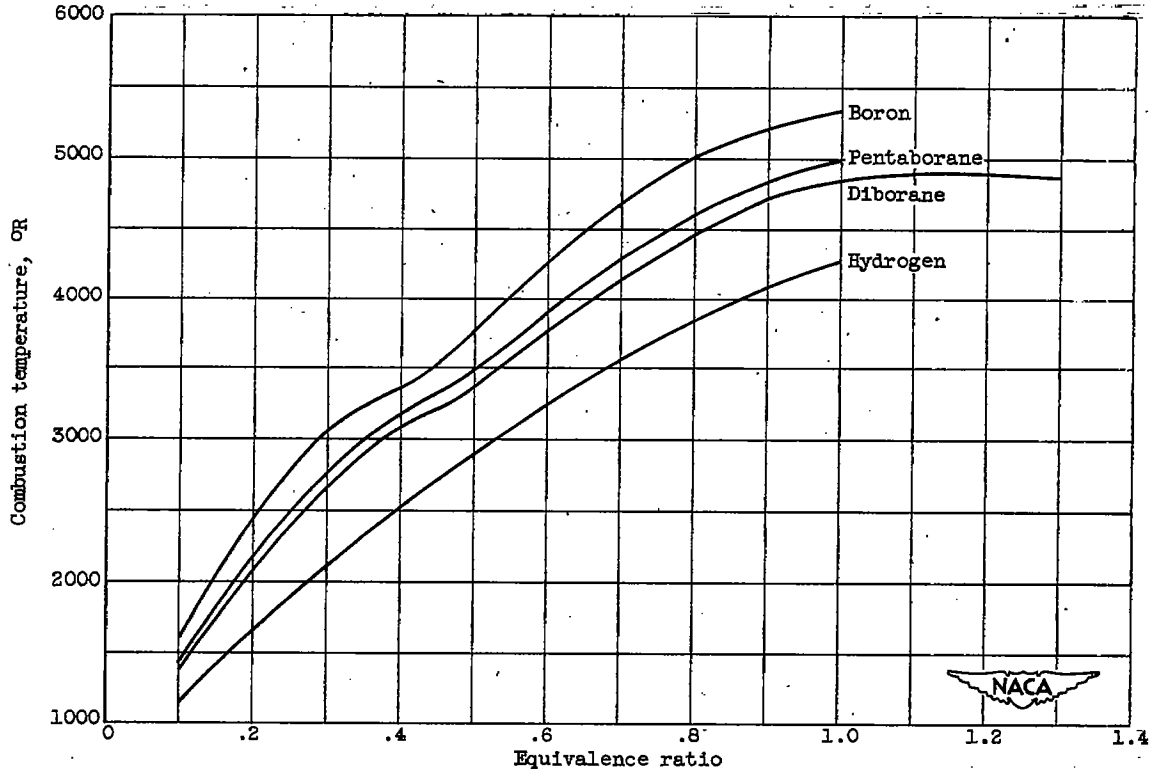
(d) Variation of fuel-weight specific impulse with air specific impulse.

Figure 4. - Continued. Theoretical combustion performance for hydrogen, carbon, α-methylnaphthalene, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



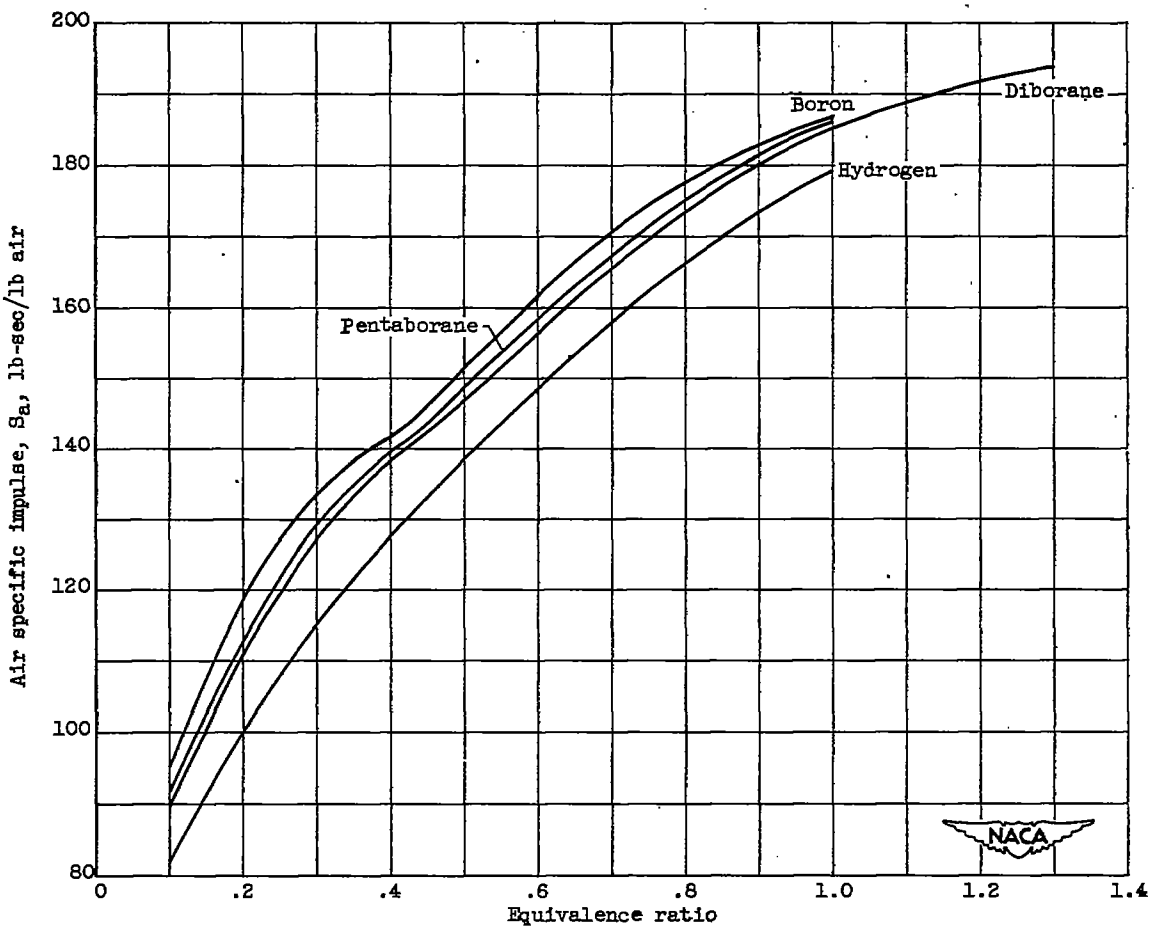
(e) Variation of fuel-volume specific impulse with air specific impulse.

Figure 4. - Concluded. Theoretical combustion performance for hydrogen, carbon, α-methylnaphthalene, and octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



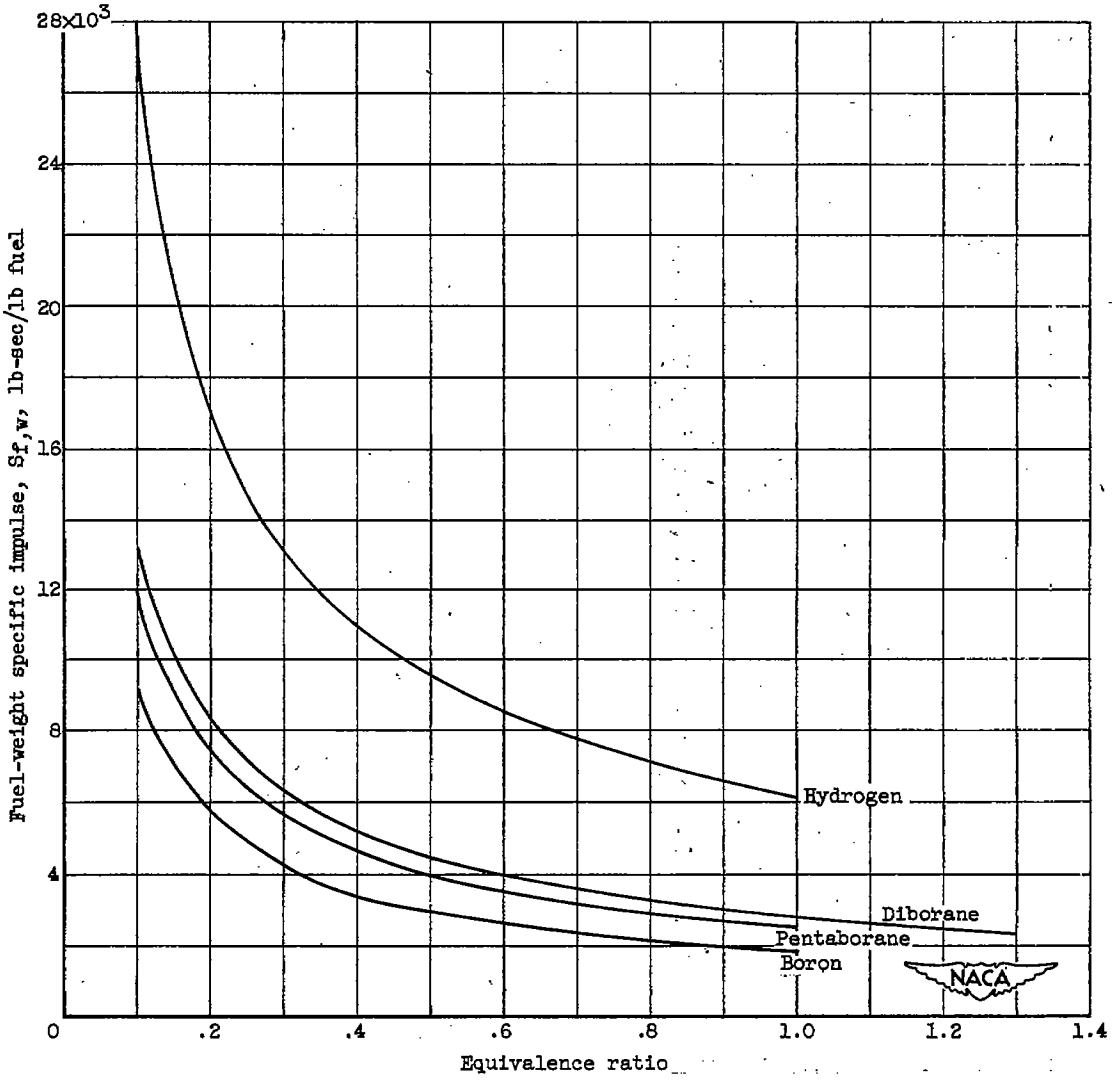
(a) Variation of adiabatic constant-pressure combustion temperature with equivalence ratio.

Figure 5. - Theoretical combustion performance of boron, pentaborane, diborane, and hydrogen. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



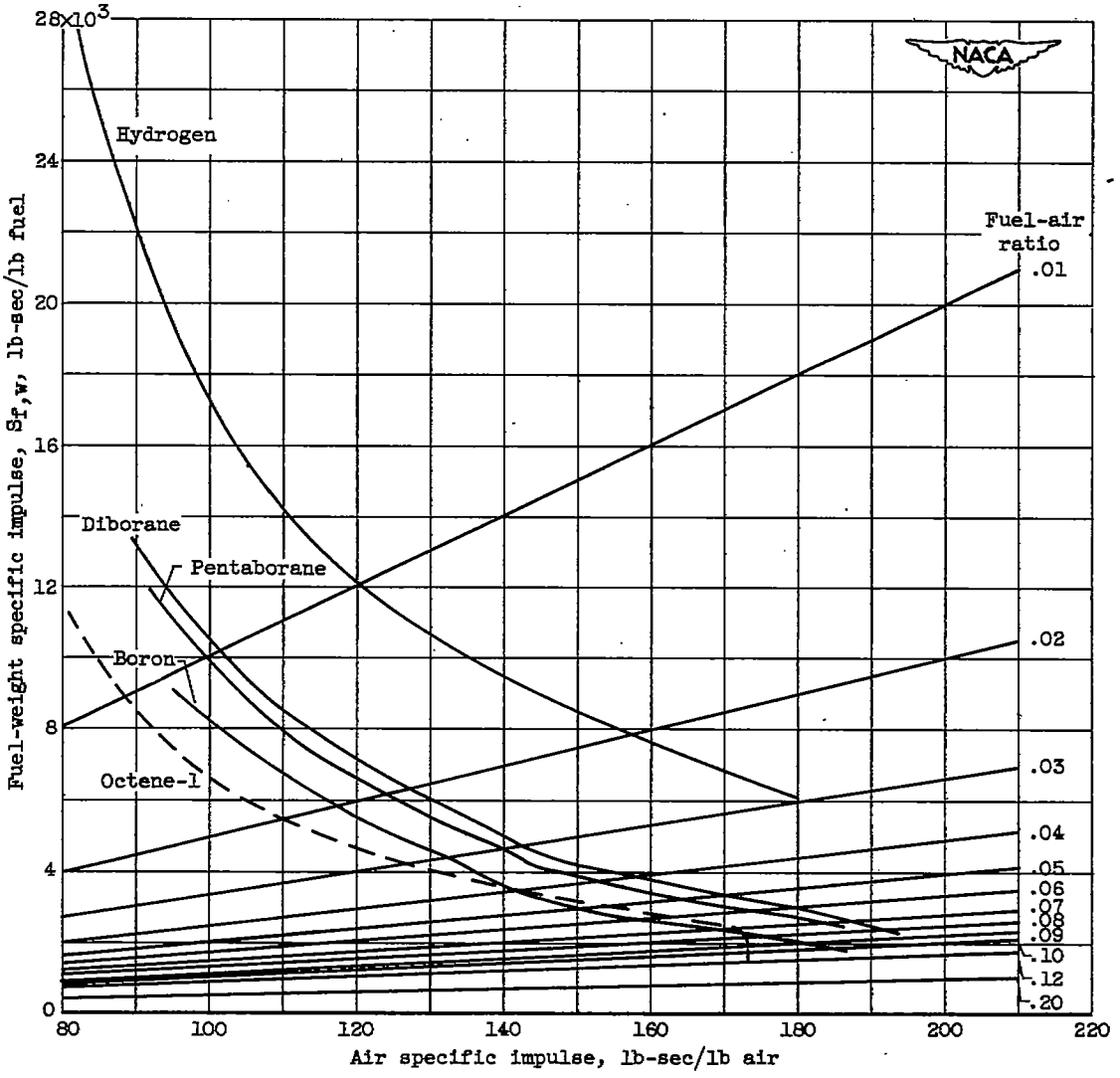
(b) Variation of air specific impulse with equivalence ratio.

Figure 5. - Continued. Theoretical combustion performance of boron, pentaborane, diborane, and hydrogen. Combustion inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



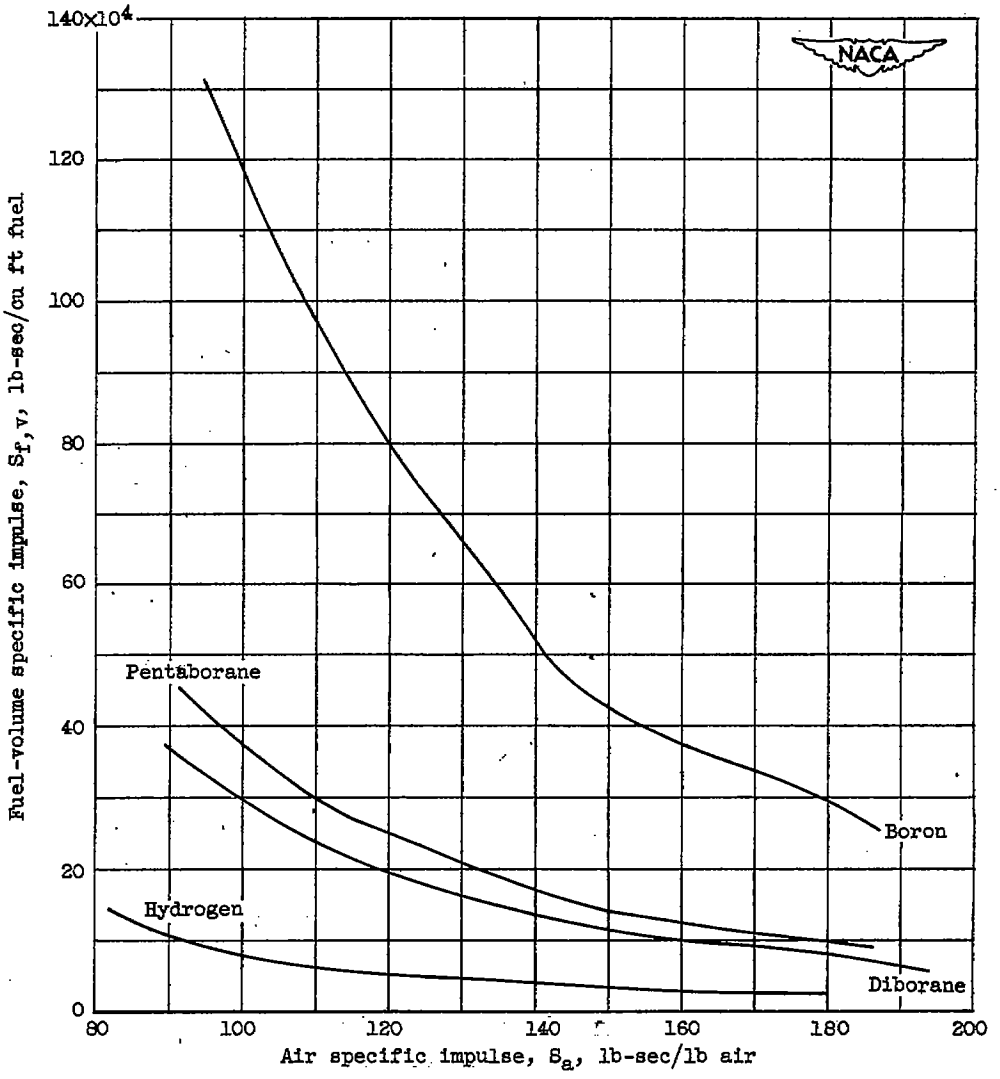
(c) Variation of fuel-weight specific impulse with equivalence ratio.

Figure 5. - Continued. Theoretical combustion performance of boron, pentaborane, diborane, and hydrogen. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(d) Variation of fuel-weight specific impulse with air specific impulse.

Figure 5. - Continued. Theoretical combustion performance of boron, pentaborane, diborane, and hydrogen. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.



(e) Variation of fuel-volume specific impulse with air specific impulse.

Figure 5. - Concluded. Theoretical combustion performance of boron, pentaborane, diborane, and hydrogen. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.

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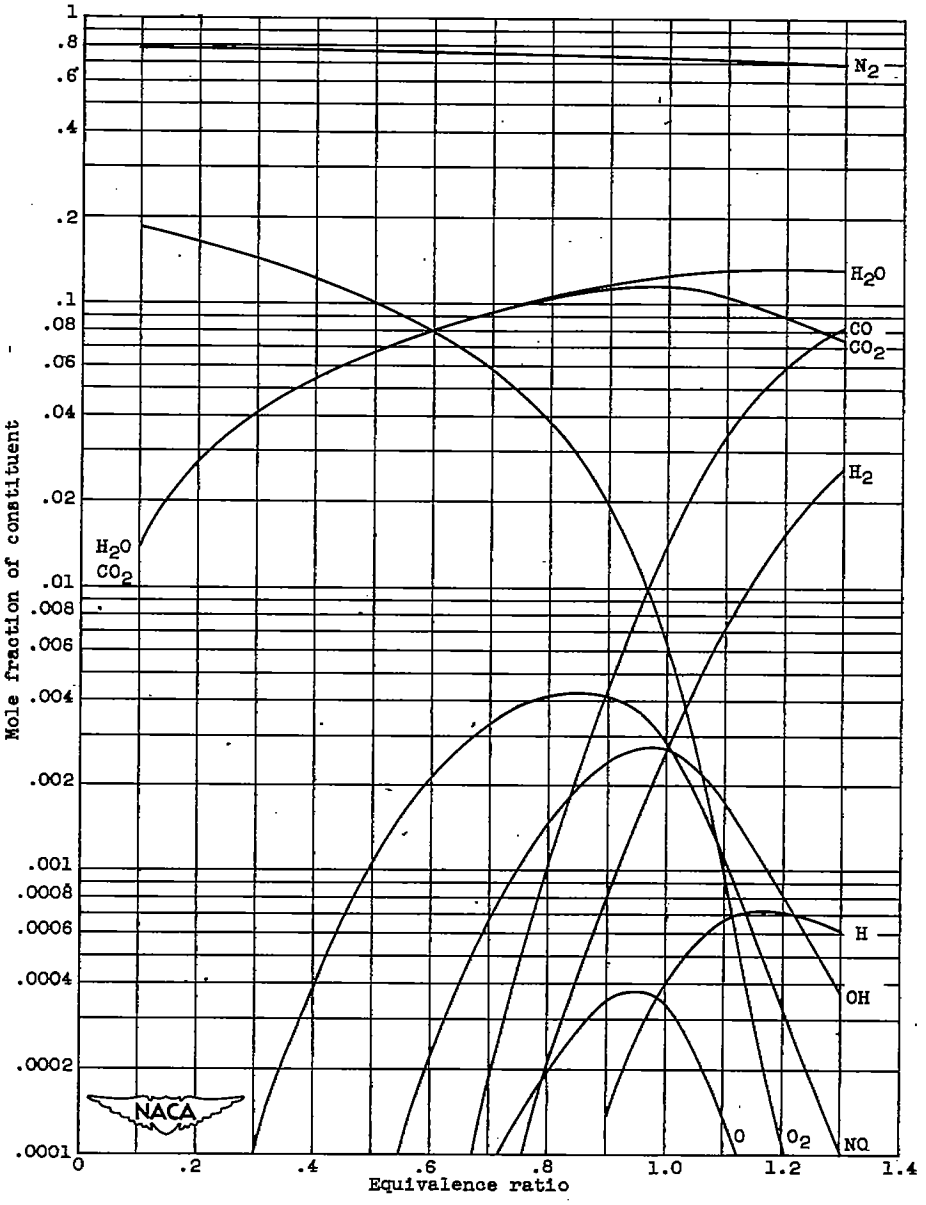
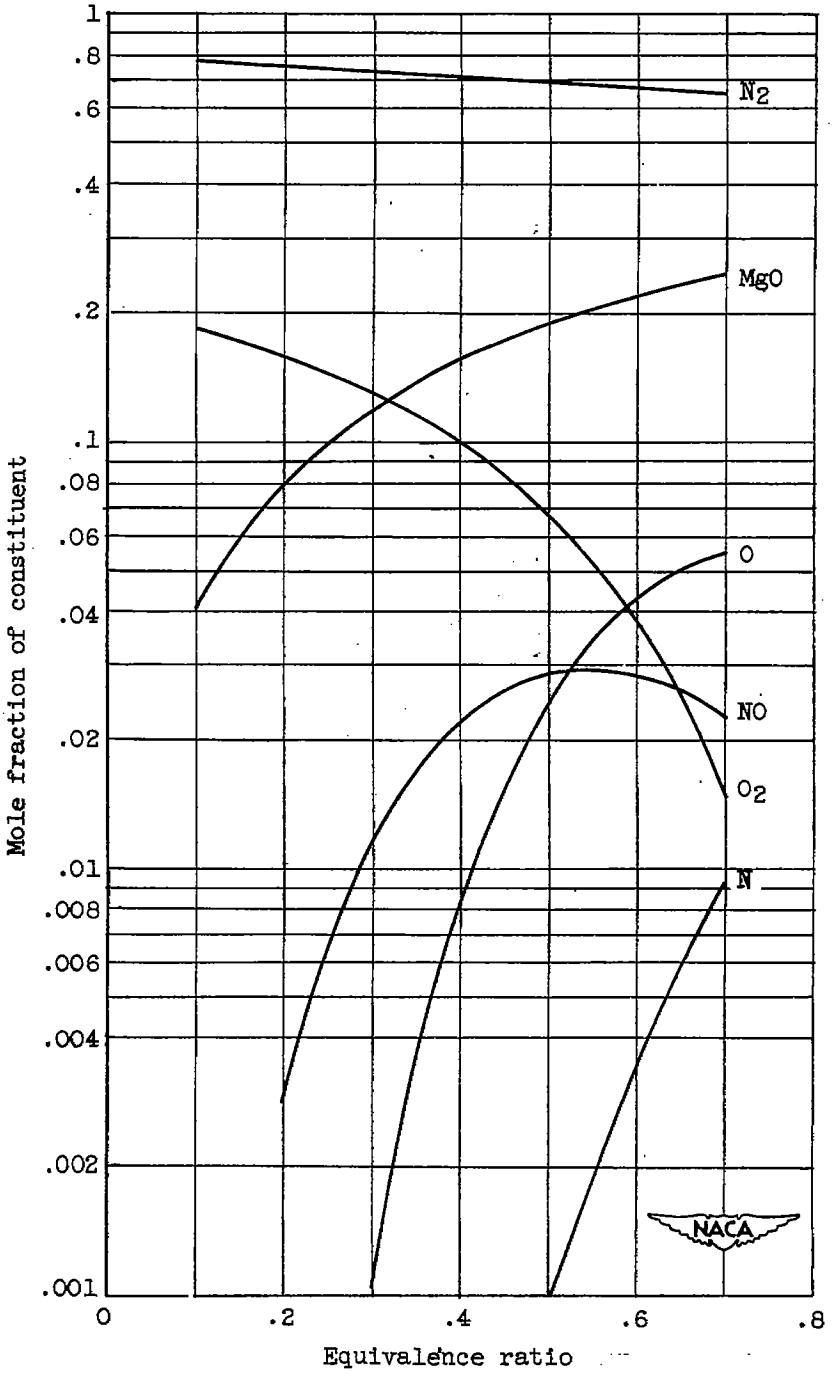


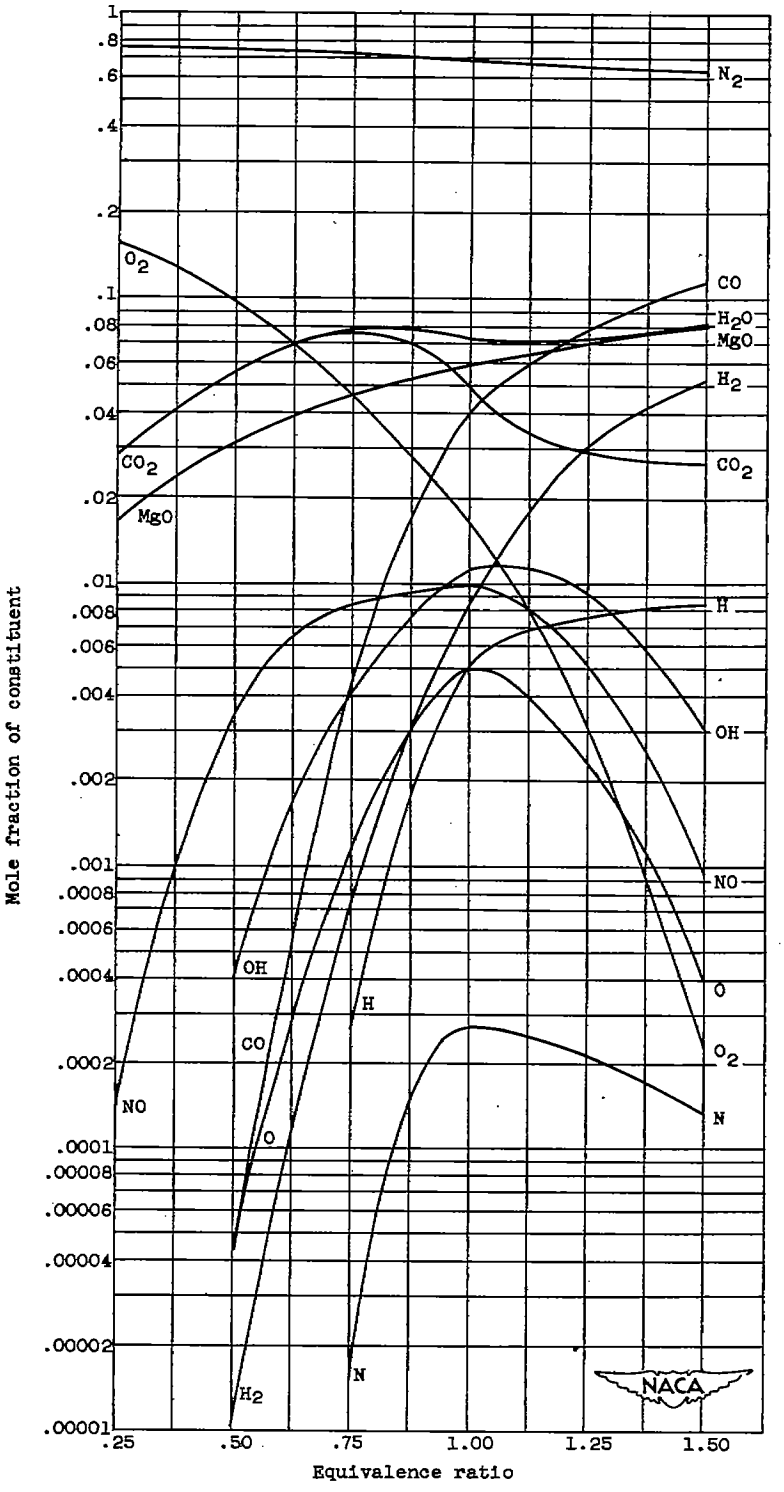
(a) Octene-1.

Figure 6. - Variation of theoretical mole fraction of constituents with equivalence ratio.



(b) Magnesium.

Figure 6. - Continued. Variation of theoretical mole fraction of constituents with equivalence ratio.



(c) 50 Percent by weight magnesium - octene-1 slurry.

Figure 6. - Continued. Variation of theoretical mole fraction of constituents with equivalence ratio.

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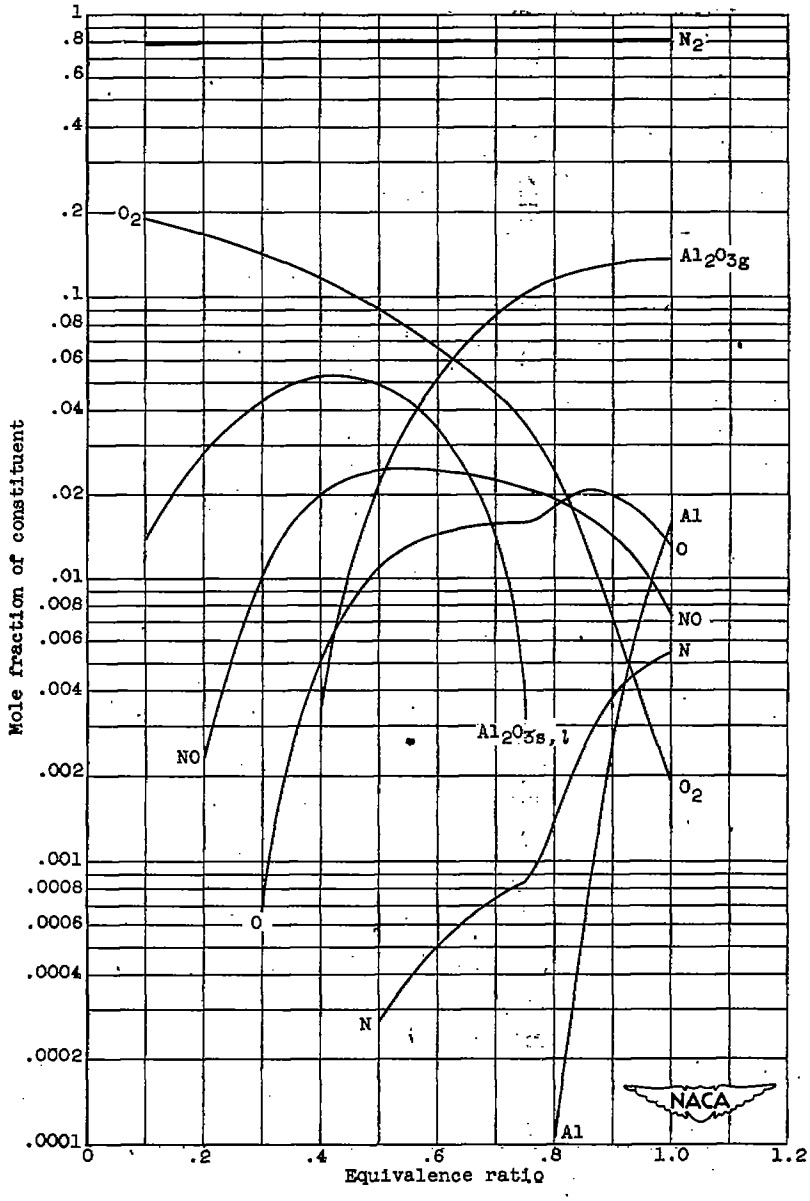
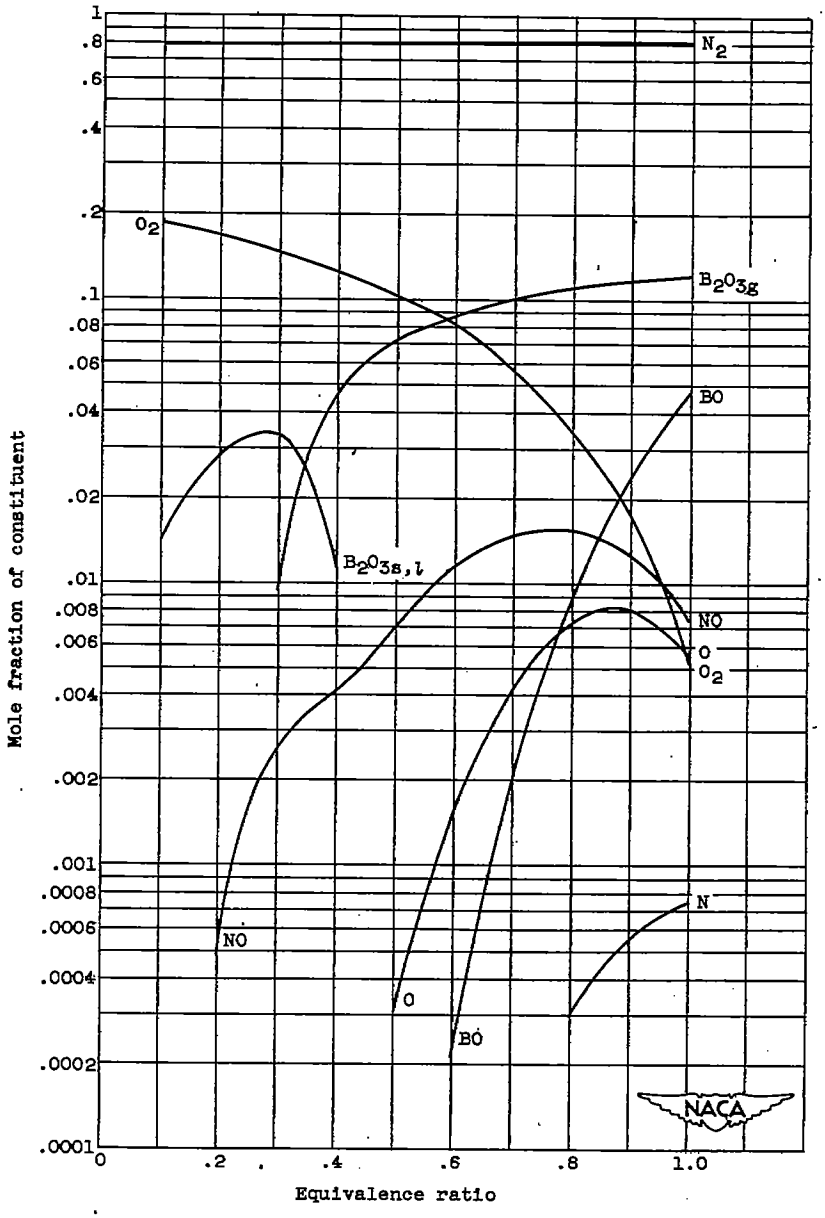


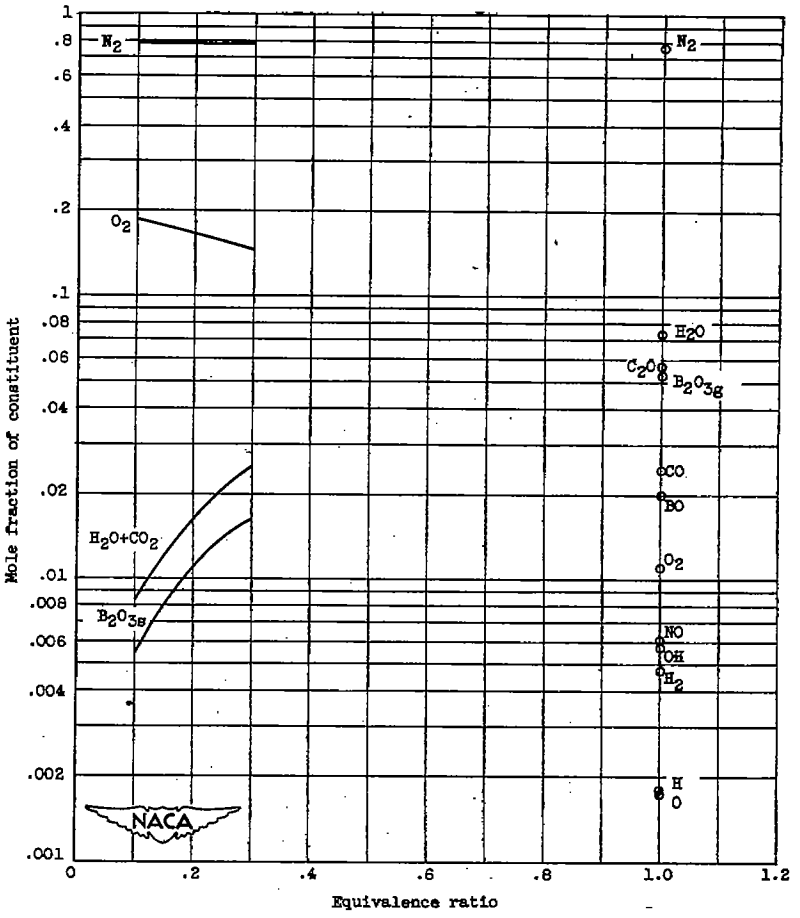
(d) Aluminum.

Figure 6. - Continued. Variation of theoretical mole fraction of constituents with equivalence ratio.



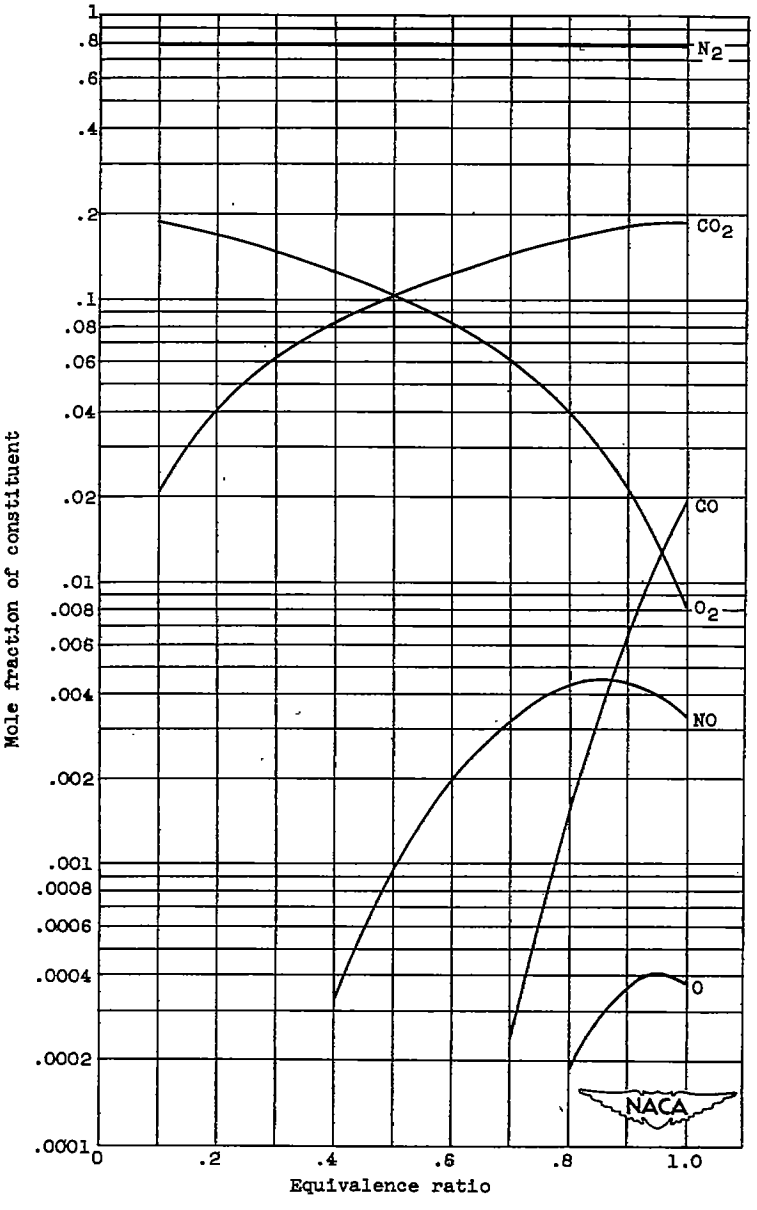
(e) Boron.

Figure 6. - Continued. Variation of theoretical mole fraction of constituents with equivalence ratio.



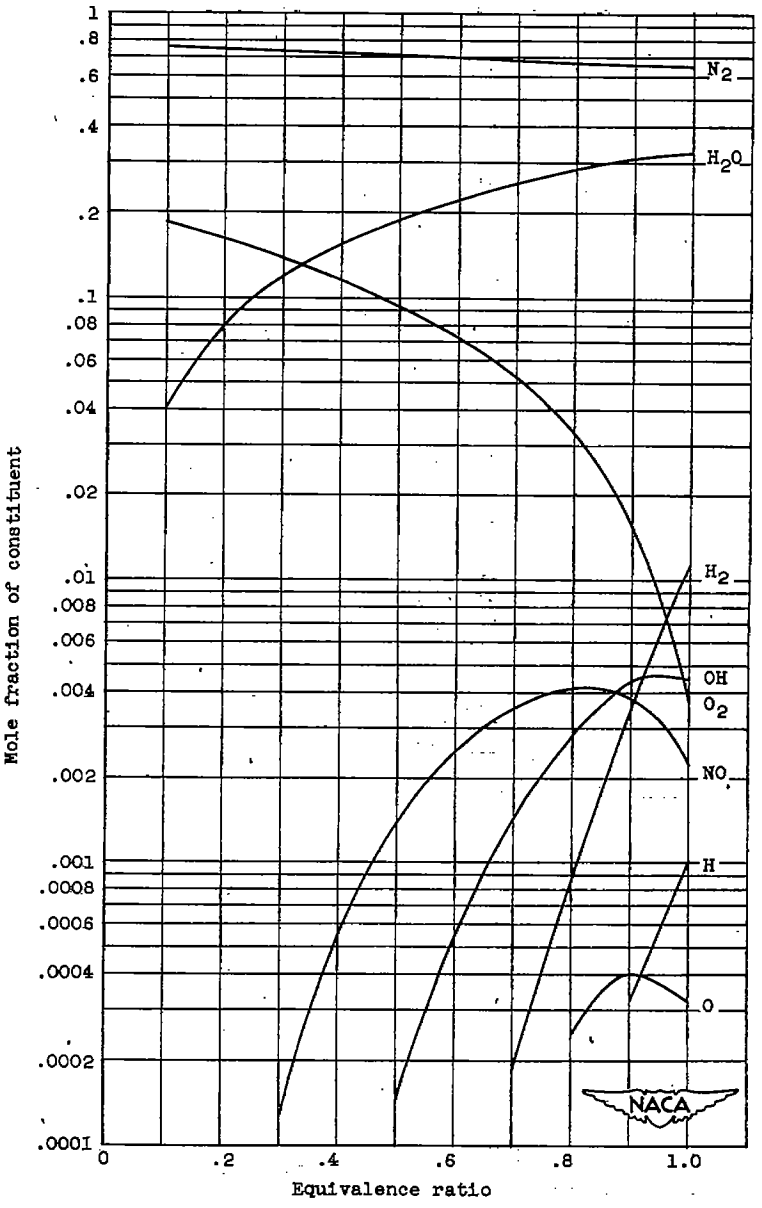
(f) 50 percent by weight boron - octene-1 slurry.

Figure 6. - Continued. Variation of theoretical mole fraction of constituents with equivalence ratio.



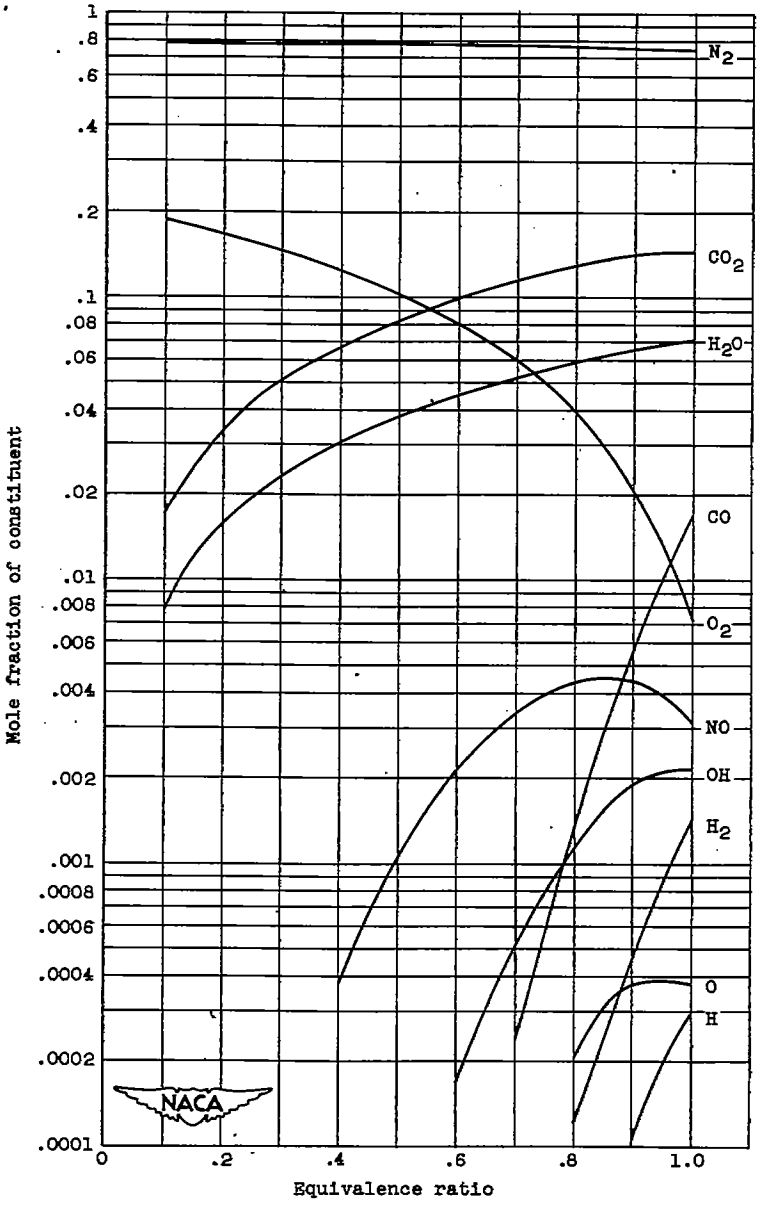
(g) Carbon.

Figure 6. - Continued. Variation of theoretical mole fraction of constituents with equivalence ratio.



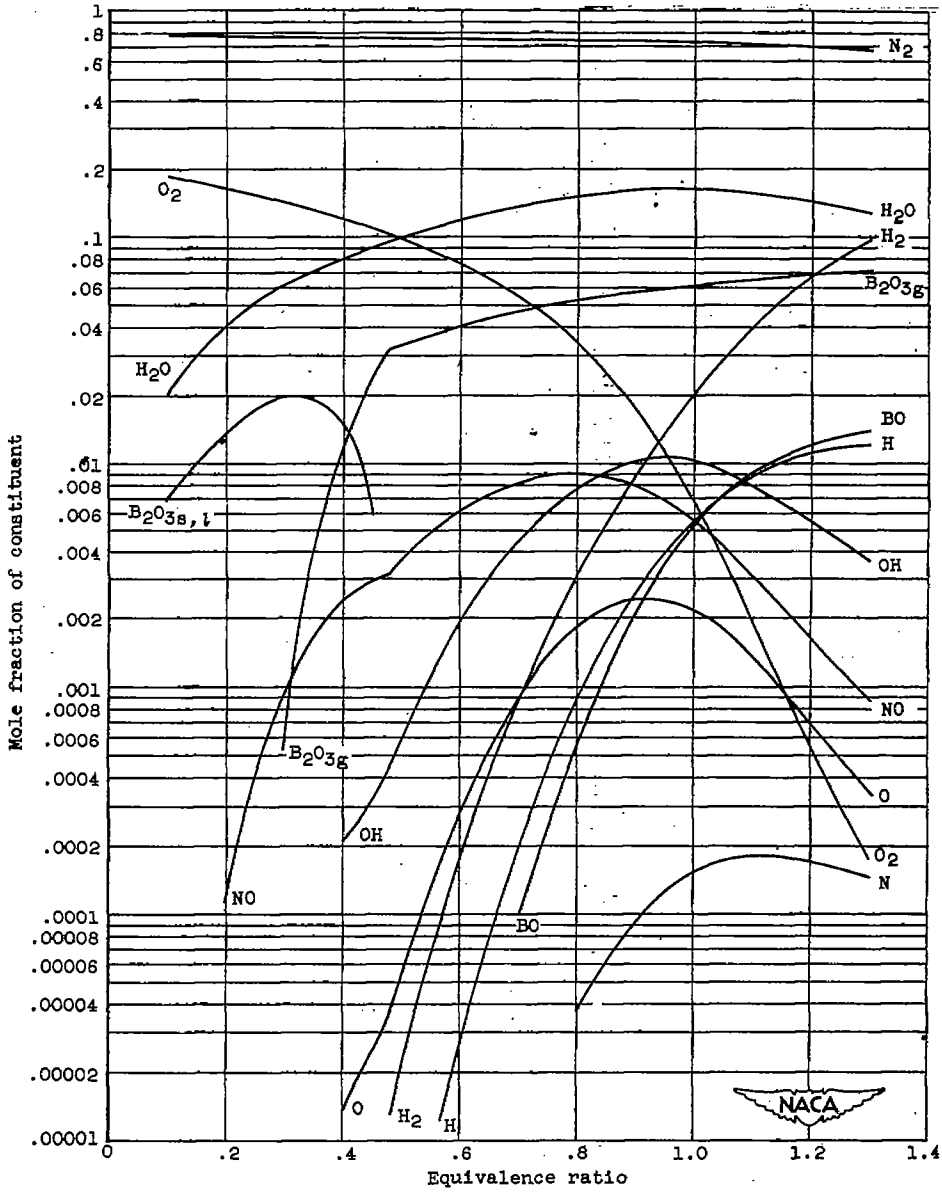
(h) Hydrogen.

Figure 6. - Continued. Variation of theoretical mole fraction of constituents with equivalence ratio.



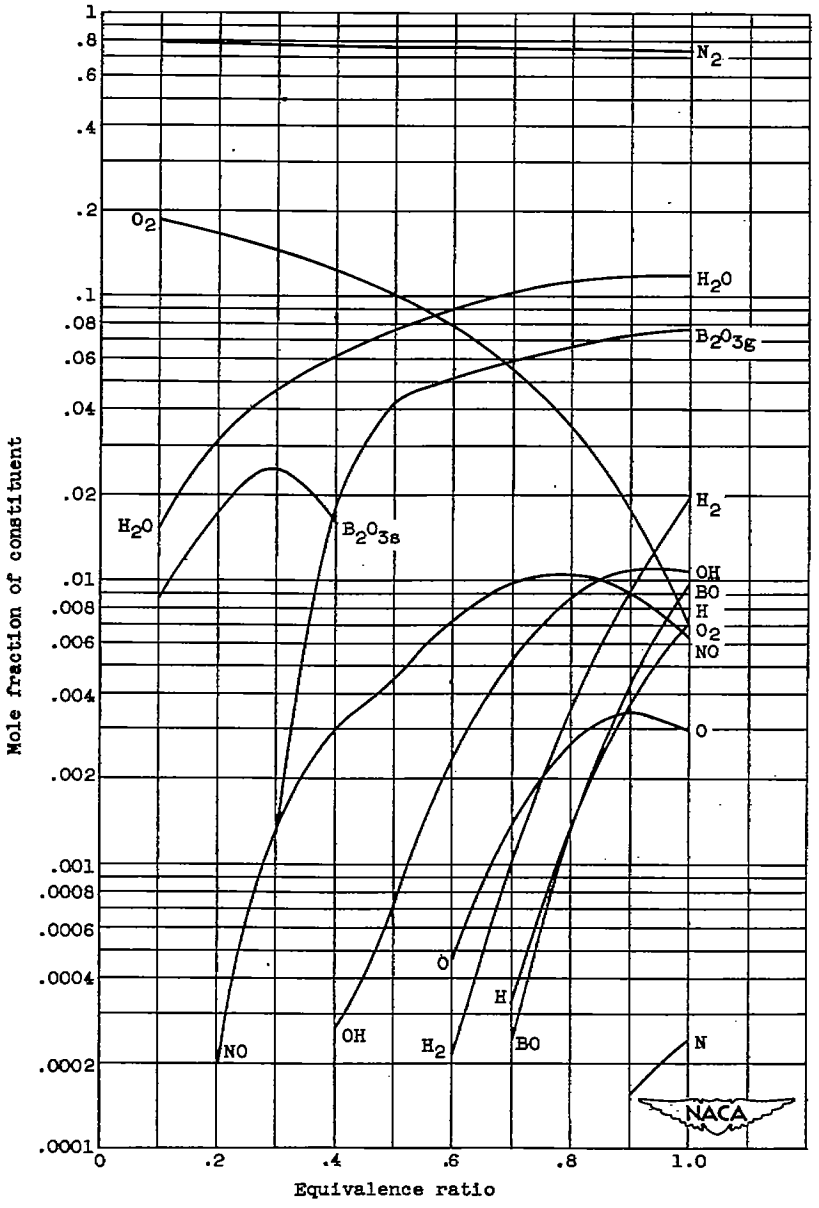
(i) α-Methylnapthalene.

Figure 6. - Continued. Variation of theoretical mole fraction of constituents with equivalence ratio.



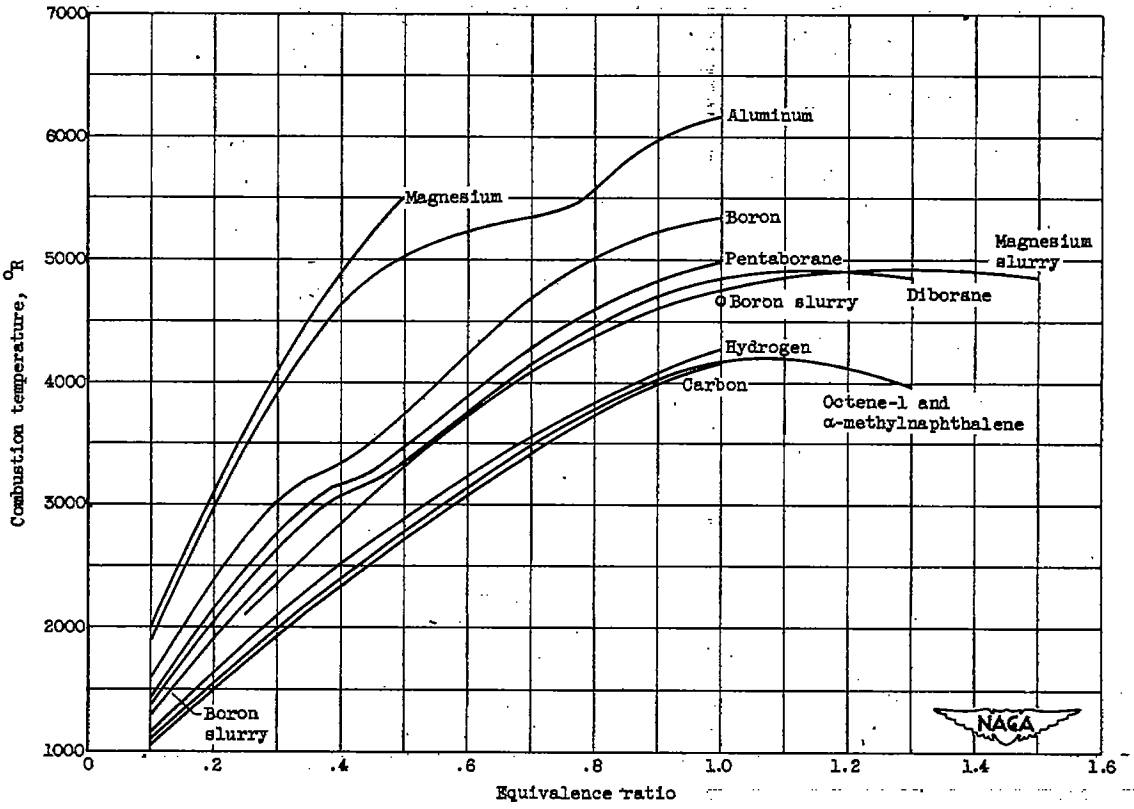
(j) Diborane.

Figure 6. - Continued. Variation of theoretical mole fraction of constituents with equivalence ratio.



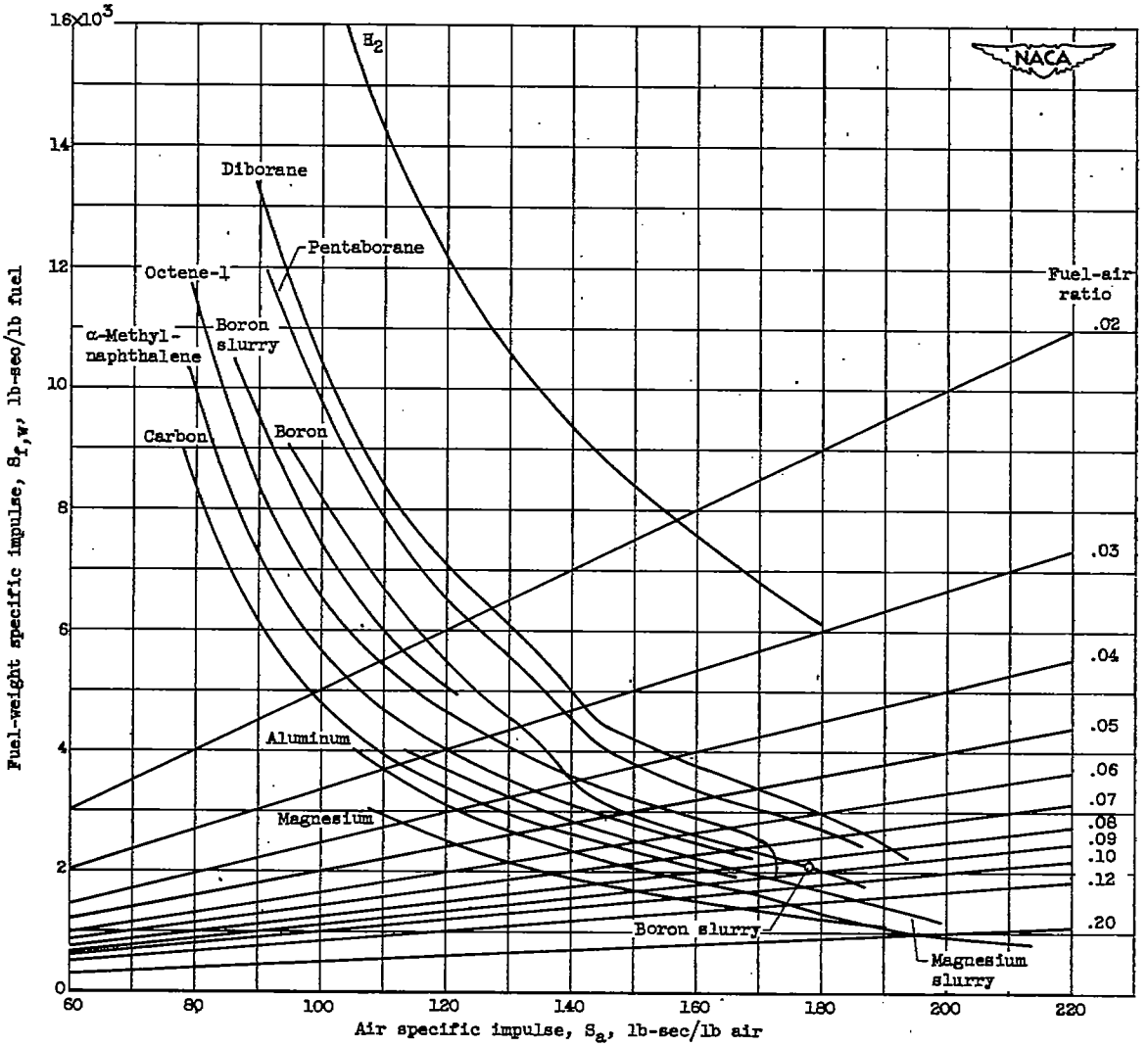
(k) Pentaborane.

Figure 6. - Concluded. Variation of theoretical mole fraction of constituents with equivalence ratio.



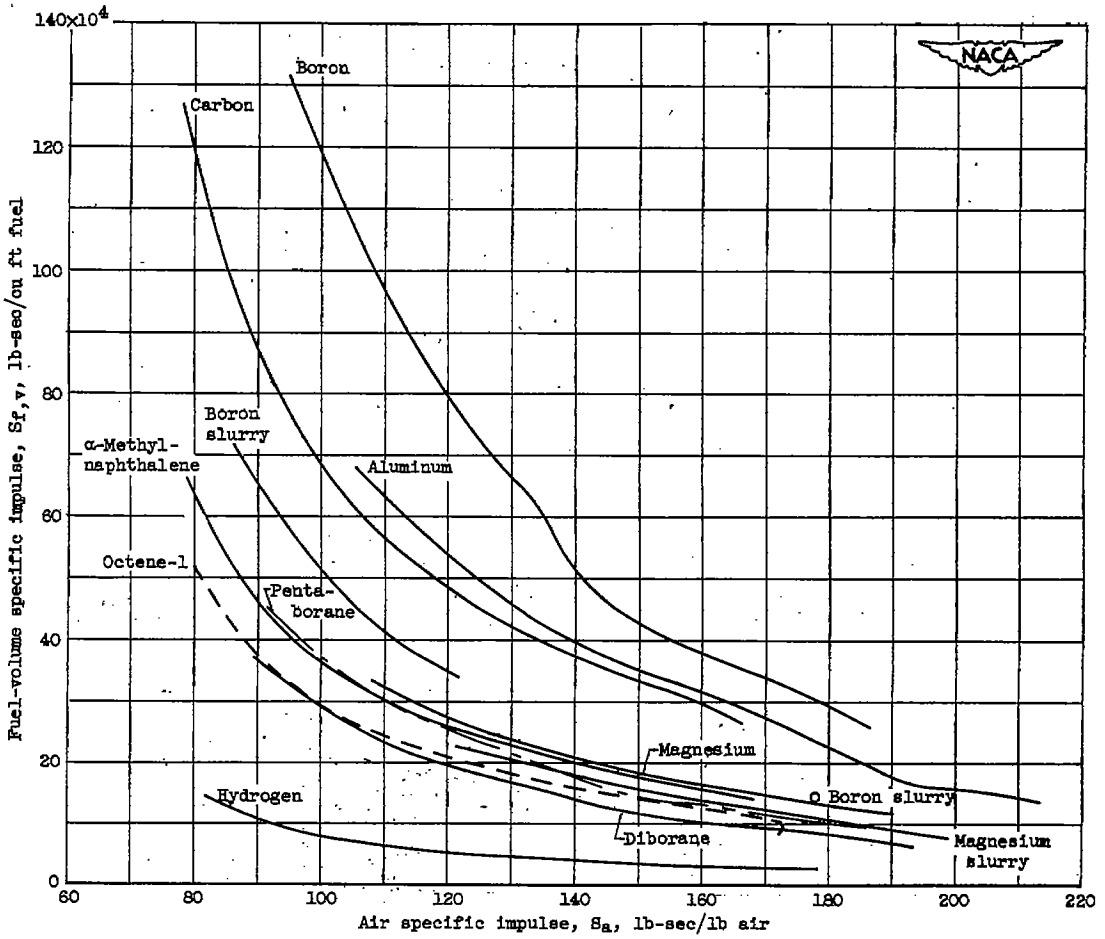
(a) Variation of adiabatic constant-pressure combustion temperature with equivalence ratio.

Figure 7. - Summary of combustion performance for representative high energy fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. (Slurry fuels, 50 percent metal by weight in octene-1.)



(b) Variation of fuel-weight specific impulse with air specific impulse.

Figure 7. - Continued. Summary of combustion performance for representative high energy fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. (Slurry fuels, 50 percent metal by weight in octene-1.)



(c) Variation of fuel-volume specific impulse with air specific impulse.

Figure 7. - Concluded. Summary of combustion performance for representative high energy fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. (Slurry fuels, 50 percent metal by weight in octene-1.)

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